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Super bursts and long bursts as surface phenomena of compact objects

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ABSTRACT

X-ray bursts from compact stars are believed to be a result of Type I thermonuclear processes which are short-lived, typically ∼10 to 100 s. There are some low mass X-ray binaries, such as 4U 1820–30, 4U 1636–53, KS1731–260 and Serpens X-1, known as super bursters (SBs) which emit X-rays close to the Eddington luminosity limit for long periods of several hours. Recently, there have been reports of some long bursters (LBs), which have bursts lasting 6–25 min, whereas 4U 1735–44 has a burst period of 86 min.

We suggest that these bursts from SBs and LBs may be a result of breaking and re-formation of diquark pairs, on the surface of realistic strange quark stars. We use the beta equilibrated u, d and s quark model of Dey et al. and Li et al. and allow for spin-dependent hyperfine interaction between quarks. The interaction produces pairing of specific colour-spin diquarks, leading to further lowering of energy by several MeV for each pair, on average.

Diquarks are expected to break up because of the explosion and shock of the thermonuclear process. The subsequent production of copious diquark pairing may produce sufficient energy to produce the very long bursts seen in SBs or LBs. We do not claim to be able to model the complicated process fully. However, the estimated total energy liberated, 10^{42} erg, can be explained in our model with the calculated pair density $\sim 0.275\ \mathrm{fm}^{-3}$ and a surface thickness of only half a μm, if the entire surface is involved. The depth of the surface involved in the process may be only few μm if the process is restricted to a small part of the surface near the equator, as suggested by Bildsten.

If SBs and LBs are surface phenomena, then recurrent super bursts, found near 4U 1636–53 by Wijnands at an interval of 4.7 yr, and the quick cooling of KS 1731–260 could be natural in this model.

Key words: dense matter – elementary particles – X-rays: stars.

1 INTRODUCTION

It is intriguing to surmise that the elusive properties of some of the most compressed objects in nature, namely compact stars, showing super bursts, may be accounted for by the spin alignment of pairs of the smallest components of matter, namely quarks.

Recently, there has been much activity centred around the possibility of lowering of the spin zero state of a diquark in dense matter; see, for example, the review by Rajagopal & Wilczek (2000) and references therein. There has also been the suggestion that diquarks may be present (Bhalerao & Bhaduri 2000) like droplets, i.e. with total negative energy rather than just a negative correlation energy as in a superconducting pair.

The large N_c expansion, for the number of colours N_c, suggests a tree-level mean-field calculation for quark matter. Using a realistic two quark potential within this scenario leads to realistic strange stars (ReSS) which are self-bound. The matter has a minimum energy at a density that is high (about four to five times the normal nuclear matter density, $\rho_0 = 0.17\ \mathrm{fm}^{-3}$) as shown in Dey et al. (1998). By a simple perturbative calculation using various sets of smeared spin–spin interactions, which were tested for the isobar–nucleon mass difference in Dey & Dey (1984), we now estimate the spin correlations in this matter, which is washed out in the mean-field approximation of Dey et al. (1998), being a $1/N_c$ effect.

The importance of the exercise may be far-reaching, in so far as there is a rich plethora of unexplained phenomena in the X-ray

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emission pattern of compact stars. For example, the compact object claimed to be ReSS (Li et al. 1999a), the SAX J1808.8–3658, shows erratic luminosity behaviour and a very long burst time (Wijnands et al. 2002). The recent discovery of the compactness of RXJ 1856.5–3754 also supports the possibility of strange stars (Drake et al. 2002).

We suggest that the structure of the surface of the star may be as important as the nature of the accretion disc variations in explaining these phenomena.

It is worth noting that, according to Kapoor & Shukre (2001), even radio pulsars are so compact that it is difficult to explain their mass and radius from neutron star models. They prefer ReSS.

2 THE ASTROPHYSICAL PROBLEM: SBS

Type I X-ray bursts in low mass X-ray binary (LMXB) systems are characterized by fast rise times (of the order of seconds), long decay times (seconds to minutes), spectral softening during the bursts, and recurrence times of hours to days. In contrast, the physics behind long-lasting 'super bursts' seen recently in several stars is not yet well known. This is mostly a result of the very recent discovery of such bursts and the limited information available about them (Wijnands 2001). The first super burst was reported by Cornelisse et al. (2000) from LMXB 4U 1735–44 in 2000. Wijnands (2001) reported on two super bursts for 4U 1636–53, and Heise, in 't Zand & Kuulkers (2000) reported on super bursts for KS 1731–4260 and Serpens X-1. For 4U 1636–53, two clear super bursts have been observed, although some of the smaller flares seen might also be related to super burst phenomena (Wijnands 2001). The full explanation of type I bursts in the stars is somewhat problematic, in so far as bursts become less frequent and energetic as the global accretion rates increase, as discussed by Bildsten (2000) recently.

Spin alignment may be spoiled during the prolonged strong accretion and the shock of the thermonuclear bursts.[1] The realignment of the spin zero diquarks could be a very natural scenario for the super bursts; this will be a slower process, because the u, d, s quark and electron percentages are equilibrated with beta stability and charge neutrality conditions involving slower weak and electromagnetic processes. The decrease of diquark energy is a strong process and the magnitude of energy release is of the same order as that of a thermonuclear reaction (TR).

Here, we outline our suggested mechanism for super bursts. Compact stars with a high rate of accretion undergo thermonuclear bursts lasting typically up to 20 s. During the high accretion and the TR, the quark pairs (in particular the ud pairs) – bound by the short-range spin–spin interaction – break. After a sufficiently long time (expected to vary substantially from star to star because of the statistical nature of the processes and also the variation of the surface conditions[2]) most of the pairs are broken. After a final TR, the pairs begin to realign.

The realignment of pairs will lead to a prolonged emission of energy, which may be transformed into X-rays leading to the super bursts. This time may also vary for the same reasons as above, thus explaining the 86-min super burst in 4U 1735–44 (Cornelisse et al. 2002), 4 h in Serpens X-1 (Cornelisse et al. 2000) and half a day in KS 1731–260 (Kuulkers et al. 2002b).

According to this scenario, there will be a link with the extreme macro physics of compact stars of sizes of the order of kilometres and masses of the order of solar masses with small diquarks paired by a short-range force of few fm and bound by few MeV. There is no time-scale limit in this model between two super bursts and we can assume that the 4.7-yr gap, between the two super bursts seen in 4U 1636–53, is the upper limit for the interval because, as a result of the erratic sampling of *Rossi X-ray Timing Explorer*/All-Sky Monitor (*RXTE*/ASM) which detected these bursts, some intermediate bursts might have been missed or partly recorded (Wijnands 2001).

4U 1820–30, which was a candidate for ReSS in Dey et al. (1998), also shows super bursts lasting 3 h, and a very interesting model has been proposed to explain this (Cummings & Bildsten 2001; Strohmayer & Brown 2001). These authors suggest that, for this particular star, which they *assume* to be a neutron star, the super bursts are a result of unstable carbon burning, the carbon possibly remaining from the ashes of a helium thermonuclear burst buried deep down (∼10 m) in an 'ocean', mixed with iron.

This is in sharp contrast to our scenario where we find enough ud quark pairs, within a depth of about 10^{-5} cm of the high-density star skin, to provide the energy of the burst – estimated by Strohmayer & Brown (2001) to be 1.4×10^{42} erg equivalent to 10^{47} MeV. The strongest constraint according to their scenario is that another such super burst should not be detected within a time-scale of less than a decade. So, if 4U 1820–30 shows another super burst within the next few months or years, the assignment of ReSS for this star (Dey et al. 1998) will find additional support from present considerations.

Thus, we find that our model provides a rather attractive alternative solution to the problem, which is also applicable to other SBs. It must be mentioned that Wijnands (2001) and Strohmayer & Brown (2001) agree that carbon burning is unlikely for 4U 1636–53 because it seems to be a hydrogen-accreting source and carbon burning is more likely for helium-accreting sources.

In the following sections, we present our model in some detail.

3 A BRIEF INTRODUCTION TO THE MODEL

The quark (q) star model described in Dey et al. (1998), which is also the same model used here, is a realistic model of quark matter composed of three flavours, u, d and s, as well as electrons. In hadron spectroscopy, using a potential model, a realistic q–q interaction contains asymptotic freedom (short range) and confinement (long range). However, in the case of quark matter, confinement is softened by Debye screening which diminishes the attractive long-range part. The effect of this screening increases with density so that deconfinement is further enhanced at high densities.

Another very important consideration is the quark masses. The general belief is that chiral symmetry tends to be restored at high density, which means that quarks become lighter. The density dependence of quark masses, therefore, is a reflection of the chiral symmetry restoration (CSR) of quantum chromodynamics (QCD) at high density. Alternatively, it can be represented as a density dependence of the strong coupling constant using simple Schwinger–Dyson techniques. We refer the interested reader to Ray, Dey & Dey (2000). The density dependence of quark masses, in this model, is taken care of by the ansatz

$$M_i = m_i + M_Q \operatorname{sech}\left(\nu \frac{\rho_{\rm B}}{\rho_0}\right), \qquad i = {\rm u, d, s} \tag{1}$$

where $\rho_{\rm B} = (\rho_{\rm u} + \rho_{\rm d} + \rho_{\rm s})/3$ is the baryon number density, $\rho_0 = 0.17\ {\rm fm}^{-3}$ is the normal nuclear matter density, and ν is a parameter.

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[1] Or the conversion of the normal accreting matter into strange matter if one prefers the other scenario for the short initial burst (Bombaci & Datta 2000).

[2] This time interval may be a few minutes [e.g. 6–25 min for the 10 super bursts observed in GX 17 + 2 (Kuulkers et al. 2002a)] or several years [e.g. 4.7 yr as in 4U 1636–53 (Wijnands 2001)].

Table 1. Properties of the maximum mass strange star configuration obtained for different forms for CSR: M_G is the gravitational (maximum) mass, R is the corresponding radius, n_c is the central number density, and ρ_c is the central mass density. Our EOS for different choices of parameters are denoted as follows: (eos1) $\nu = 0.333$, $\alpha_0 = 0.20$; (eos3) $\nu = 0.286$, $\alpha_0 = 0.20$. The reference for the binding per baryon B.E./A is 930.6 MeV for Fe^{56}.

EOS	M_G ($M_\odot$)	R (km)	n_c (fm^{-3})	ρ_c (10^{14} g cm^{-3})	B.E./A MeV
eos1	1.437	7.06	2.324	46.90	888.8
eos3	1.410	6.95	2.337	48.19	844.6

At high ρ_B, the quark mass M_i falls from its constituent value M_Q to its current one m_i, which we take to be (Dey et al. 1998): $m_u = 4$ MeV, $m_d = 7$ MeV, $m_s = 150$ MeV, with $M_Q \sim 310$ MeV. Possible variations of the CSR can be incorporated in the model through ν.

With these two ingredients (along with the constraints of beta-equilibrium and charge neutrality) it is found that energy per baryon is lower than that of ^{56}Fe and has a minimum at a density of about four to five times the normal nuclear density ρ_0. This is a relativistic mean-field calculation with a central potential (screened Richardson potential) where only the Fock term contributes. Thus, strange quark matter is, itself, self-bound by strong interaction. The energy density and pressure of this matter lead to a strange quark star through the Tolman–Oppenheimer–Volkoff (TOV) equation with mass and radius depending on the central density of the star.

Equations of state obtained for two different values of ν, which we call eos1 and eos3, lead to different maximum masses of the stars and their corresponding radii (Table 1). Table 1 also gives the energy/baryon of the strange quark matter to be compared with that of ^{56}Fe.

The surface of the star starts at this high density of about four to five times the normal nuclear density ρ_0. The density inside the star can be larger, with the limit being $\sim$15 times at the core when gravitational instability sets in. Thus, at the surface there are massive quarks (about 100 MeV for u, d and 250 MeV for s) whereas at the centre of a massive star with density $\sim$10 to 15 times the normal density ρ_0 the masses approach the current quark masses 4, 7 and 150 MeV for u, d and s, respectively).

4 THE SPIN–SPIN POTENTIAL

The Δ isobar is an isospin 3/2 of the spin-3/2 excitation of the nucleon seen at about 1232 MeV. To calculate the isobar–nucleon mass difference (of about 300 MeV) we need a finite-range spin–spin interaction. Indeed, the quark–quark interaction also has a spin-dependent component, which can be obtained either from the one-gluon exchange between quarks or from the instanton-induced interaction. This part of the potential is of delta-function range, which can be transformed to a smeared potential by introducing the idea of either a finite glue-ball mass or a secondary charge cloud screening as in electron physics (Bhaduri, Cohler & Nogami 1980).

The essential idea is to obtain a smeared Gaussian potential with a renormalized strength. The smearing and the strength can be obtained by fitting them to observables, such as nucleon–Δ mass splitting, and the magnetic dipole transition from Δ to nucleon. We borrow the allowed sets from Dey & Dey (1984).

The form of the potential is given as

$$H_{i,j} = -\frac{2\alpha_s\sigma^3}{3m_i m_j \pi^{1/2}} (\lambda_i \lambda_j)\ (S_i S_j) \exp\left(-\sigma^2 r_{ij}^2\right) . \qquad (2)$$

Table 2. Parameters of the Gaussian potential.

Sets	α_s	σ (fm^{-1})
1	0.50	6.00
2	0.50	4.56
3	0.87	6.00
4	0.87	2.61
5	1.12	6.00
6	1.12	2.03

The factor $\sigma^3/\pi^{1/2}$ normalizes the potential. In this equation, α_s is the strong coupling constant, and the m, λ and S are the mass, colour matrix and spin matrix for the respective quarks.

For u, d quarks, Dey & Dey (1984) found that this gives σ varying from 6 to 2.03 fm^{-1} for a set of α_s from 0.5 to 1.12. The parameters we have used are given in Table 2.

It is found that diquark binding depends strongly on the strength and range of spin–spin interaction, which are interconnected via hadron phenomenology. This is irrespective of whether it is deduced from a Fermi–Breit inter-quark force or an instanton-like four fermion interaction, as discussed, for example, in Rajagopal & Wilczek (2000).

5 THE EFFECT OF THE POTENTIAL ON DIQUARKS

The antisymmetry of the flavour symmetric diquark wavefunction requires that, while the space part is symmetric, the diquark must be either in a spin-singlet and colour-symmetric (6) state, or in a spin-triplet and colour-antisymmetric ($\bar{3}$) state. In both cases, the spin–spin force is repulsive[3] and pair formation is inhibited.

For flavour antisymmetric diquarks, however, the situation is the opposite. The colour-symmetric 6 configuration is associated with the spin triplet so that $(\lambda_i\lambda_j)(S_i S_j) = 1/3$ and the colour-antisymmetric state ($\bar{3}$) goes with the spin-singlet state, giving $(\lambda_i\lambda_j)(S_i S_j) = 2$. With the overall negative sign in the potential equation (2), these channels produce attraction. Hence there is a probability, for example, for u, d quarks to pair up predominantly in the spin-singlet state. The effect of this can be found easily in our model, because we know the distribution of the u, d and s quarks in the momentum space and their Fermi momenta are uniquely determined from precise and lengthy calculations satisfying beta stability and charge neutrality.

In addition to the spin-colour contribution, the potential equation (2) is evaluated in the momentum space

$$\frac{1}{4\pi^3 3x\rho_0} \frac{\alpha_s\sigma^2}{3m_i m_j} \int f(k) k_i^2 k_j^2 \, \mathrm{d}k_i \, \mathrm{d}k_j \, \mathrm{d}\cos(\theta) \qquad (3)$$

where $x\rho_0$ is the density at the star surface where the energy per baryon is minimum ($x = 4.586$ and 4.014 for eos1 and eos3):

$$f(k) = \frac{1 - \exp\left(\frac{-k^2}{\sigma^2}\right)}{k^2} \qquad (4)$$

and

$$k^2 = \frac{k_i^2 + k_j^2}{4} - \frac{k_i k_j \cos(\theta_{ij})}{2}. \qquad (5)$$

It should be noted that Fermi momenta for u, d and s particles are different. Thus, the contribution of a specific diquark in the energy

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[3] Private communication, R. K. Bhaduri.

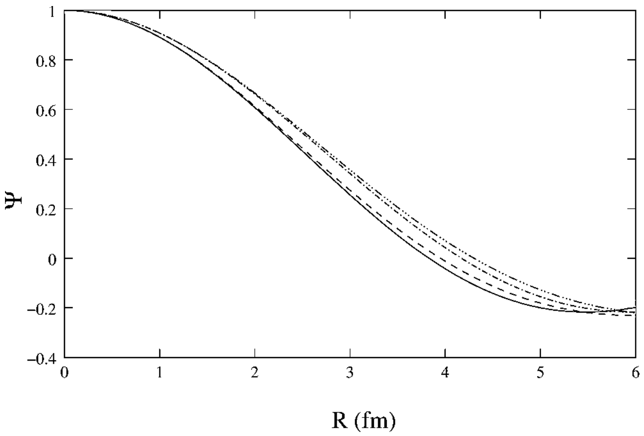

Figure 1. The figure shows the similarity between the spherical Bessel function and the appropriate oscillator wavefunctions. The top pair of curves correspond to $\cos(\theta) = 1$ in equation (5) and the bottom curves to $\cos(\theta) = -1$. The oscillator in both cases is the upper curve of the pair. The values of relative k are 0.75 and 0.82 fm^{-1}, respectively. At such relatively large momenta, very little angular dependence is seen.

Table 3. Integrated values for the pairing energy [equation (2)] for different pairs of spin-singlet (colour $\bar{3}$) states in MeV. For the spin-triplet (colour 6) state, the energies will be six times less.

EOS	Sets	α_s	σ (fm^{-1})	Diquark type ud	ds	su
eos1	1	0.50	6.00	−3.84	−1.45	−1.23
	2	0.50	4.56	−3.79	−1.44	−1.22
	3	0.87	6.00	−6.68	−2.53	−2.22
	4	0.87	2.61	−6.22	−2.37	−2.02
	5	1.12	6.00	−8.59	−3.25	−2.76
	6	1.12	2.03	−7.59	−2.89	−2.48
eos3	1	0.50	6.00	−3.87	−1.40	−1.15
	2	0.50	4.56	−3.83	−1.39	−1.17
	3	0.87	6.00	−6.74	−2.44	−2.06
	4	0.87	2.61	−6.32	−2.29	−1.95
	5	1.12	6.00	−8.68	−3.14	−2.65
	6	1.12	2.03	−7.74	−2.82	−2.40

can be simply the integral (3) and the colour spin factor. However, the maximum contribution is around the Fermi surface (see Table 3).

Note that there is a difference between this energy and the conventional pairing, where the effect of a long-range potential is a shift that is found by solving the gap equation. This is more like a correlation energy for some of the paired diquarks in the flavour antisymmetric state. The possibility of this kind of correlation arises from the similarity (Fig. 1) between oscillator wavefunctions typical for bound states and spherical Bessel functions typical for scattering, for small distances.

Table 3 shows that the variation of the correlation energy is significant when different sets for the smearing in the spin–spin potential are chosen. The variations of eos1 and eos3 are comparatively unimportant.[4] We also see that the ud pairing correlation energy is substantially larger than that of the other pairs, su and ds.

Let us recall that the energy per baryon is 888.8 MeV with eos1 and 844.6 MeV with eos3, compared to 930.4 MeV for ^{56}Fe matter. We can see that, even in the preferentially ordered spin-singlet state, there are only a few MeV extra binding on average for every diquark, compared to a positive energy of several hundred MeV.

However, we should not forget that, in a TR, every fusion produces energy which is precisely of this order. On the other hand, a TR is fast, and it must take a long time to establish a stable high density of about 4.5 times ρ_0 and to retrieve the ordering of the diquarks after a TR. If it is established that the concerned stars are indeed strange stars and the diquark pairing is the phenomenon responsible for long-lasting bursts, then we could claim a link between the smallest quarks and the densest stars, as has been pointed out previously (Ray et al. 2000).

6 CONCLUSIONS AND SUMMARY

Our calculations teach us the following:

(1) There are antisymmetric diquark states for dissimilar quark pairs in the spin parallel and antiparallel states with an attraction six times stronger for the latter compared to the former. But the magnitude of the attraction depends strongly on the form of the interaction, even when the interaction is fitted to observables such as the standard isobar–nucleon mass difference.

(2) However, the six parameter sets that we have considered all show an attraction of a few MeV so that it is comparable to other strong interaction phenomena such as the energy release per particle in a thermonuclear burst. Because our model consists of realistic strange stars with quarks at the surface and not in the interior as in hybrid neutron stars, there is bound to be an observable surface phenomenon. Indeed we find a surface thickness of half a micron to liberate the estimated energy, 10^{42} erg (Strohmayer & Brown 2001).

(3) The interaction producing a coloured diquark in the spin-zero state, for example, is a strong one and its overall effect is the decrease of energy by 2–7 MeV. Once the pairs are misaligned as a result of high-level accretion of some binary stars and subsequent violent thermonuclear reactions (lasting typically for ~20 s), their recombination may provide bursts over several hours with the energy release estimated to be large. The crucial fact is that the recombination time-scale is long, because the strong interaction pairing process is supplemented by beta equilibrium and charge neutralization, which are slower weak and electromagnetic processes. The number of pairs is shown to be right to produce the estimated energy release for 4U 1820–30.

(4) The alternative to this calculation is to consider the full 16-component Dirac wavefunction for the diquark in a manner performed by Crater & van Alstine (1984) using the Dirac constraint method for the two-body Dirac equation. This is clearly beyond the scope of the present paper, which is concerned more with phenomenology. In such a calculation, the effect of the spin–spin force will be manifest in the mean-field level with more complicated spin wavefunctions but we are not sure if such states can be used to generate solutions of the TOV equations.

In summary, we suggest that the super bursts (sometimes repeated), lasting many hours, may be a result of the breaking of dissimilar quark pairing in a specific coloured state in strange quark stars, following conventional quick thermonuclear bursts and their subsequent recombination. If strange stars are confirmed from astro-phenomenology, such considerations may prove to be very useful.

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[4] As stated before, these EOS differ only by one parameter, which controls the chiral symmetry restoration for the quark masses at high density (Dey et al. 1998).

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