STRANGE STARS AND SUPERBURSTS AT NEAR-EDDINGTON MASS ACCRETION RATES

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\textbf{ABSTRACT}

Careful assessment of four good superburst candidates for GX 17+2 reveals that superburst is possible at near Eddington mass accretion rates. For the other seven stars, where superburst is found, there is the standard model of burning accumulated carbon from normal type I bursts of the accreting stars. However, there is the need for carbon, nitrogen and oxygen mass fraction \(Z_{CNO}\) which must be larger than \(Z_{CNO,\odot}\), where the latter refers to the standard value found in the sun. Also it is very difficult to incorporate GX 17+2 into the standard picture of superbursts. In case of superbursts from strange stars, arising from broken quark pairs going over to diquarks at the surface of the star, these problems do not arise. Furthermore there is a natural explanation for the large value of \(\sim 1000\) for \(\alpha\) which is defined in the literature as the ratio of energy released between normal bursts to the energy released during the normal burst. In the scenario for superbursts in strange stars it may be argued that the relatively smaller value of \(\alpha\) of \(\sim 440\) indicates frequent recurrence of superbursts which is reflected in 4U 1636–53.

\textit{Subject headings:} diquark pairs– stars: strange matter – stars: superbursts – pairing interaction – X rays

1. \textbf{INTRODUCTION}

Type I X-ray bursts from Low Mass X-ray Binary (LMXB) systems are believed to be due to the thermonuclear fusion. The duration of such bursts is typically of the order of seconds to minutes. Recently some such Type I X-ray bursters show bursts three orders of magnitude more energetic also longer by same factor compared to type I X-ray bursts. That is why they are known as long bursts. Also for their large fluences they are often referred as superbursts.

Eight different superbursts have been detected with accretion rate \((0.1-0.3) \times M_{\text{Edd}}\) (Eddington mass accretion rate). They are from 4U 1735–44 \cite{Cornelisse et al. 2000}, Serpens X-1 \cite{Cornelisse et al. 2002}, KS 1731–26 \cite{Kuulkers et al. 2001}, GX 3+1 \cite{Kuulkers et al. 2001}, 4U 1820–30 \cite{Strohmayer and Brown 2002}, 4U 1636–53 \cite{Wijnands 2001} and 4U 1254–69 \cite{in’t Zand et al. 2003}.

All of them show some common typical features, like all superbursters are known Type-I X-ray bursters; the burst duration is long \(\sim\) few hours; burst energy is large - of the order of \(10^{42}\) ergs; there exists a persistent preburst luminosity \((0.1-0.3) \times L_{\text{Edd}}\). It was believed that there are no super burst from sources with persistent luminosity less than \(0.1L_{\text{Edd}}\)

and greater than \(0.5L_{\text{Edd}}\). However four superbursts were reported from GX 17+2 in March 2004 \cite{in’t Zand et al. 2003}. One of the seven superbursters, 4U 1636–53, has shown repeated superbursts in a time interval 4.7 years \cite{Wijnands 2001} and 4 superbursts were reported from GX 17+2 in 4.7 years \cite{in’t Zand et al. 2003}. The shortest observed recurrence time is 8.2 days.

The characteristics of the seven superbursters known so far are given in Table 1. We have excluded the source GX 17+2 here.

We have used the strange star model proposed by Dey et al. (1998) and which has been used by Li et al. (1999a) for compactness and Li et al. (1999b) and Mukhopadhyay et. al. (2003) for quasi-periodic oscillations in the power spectrum. This model uses an interquark potential which has asymptotic freedom, confinement - deconfinement transition built into it and uses density dependent quark mass. The beta stability and charge neutrality demand a self consistent calculation of the chemical potentials of the quarks and electrons since interquark interaction is present and also involves contribution from density dependence of quark mass an gluon screening length. Diquark pairing and pair breaking in this model has been used as

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a source to explain superbursts (Sinha et al. 2002).

The standard explanation of superbursts for neutron star candidates is in the form of carbon burning. This has been studied in detail (e.g., by Cooper et al., 2005) where some earlier references may also be found. This recent work states that clearly the observations of GX 17+2 are inconsistent with their results but that the issue should be investigated further. These authors also leave out the system 4U 1820−303 in which the accreted matter is dominated by helium but point out that it is not understood theoretically why this system does not exhibit normal bursts for long periods when the accretion is near its maximum. As already mentioned a further problem is that the (bursts for long periods when the accretion is near its maximum.

We get a spin-spin potential between quarks in specific colour channels with a smeared Gaussian potential with a renormalized strength. The smearing and the strength can be obtained by fitting them to observables like 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

$$H_{ij} = -\frac{2\alpha_s\sigma^3}{p_{m,j}N_c}G^{ij}(\lambda_i, \lambda_j)\delta_{ij}e^{-\sigma^2r_{ij}}.$$  \hspace{1cm} (1)

The factor $\sigma^3/N^{1/2}$ normalizes the potential. In this equation $\alpha_s$ is the strong coupling constant, and the subscripted $m, \lambda$ and $S$ are the constituent masses, colour matrices and spin matrices for the respective quarks. For $u-d$ quarks this gives $\sigma$ varying from 6 to 2.03 fm$^{-1}$ for a set of $\alpha_s$ 0.5 to 1.12 (Dev and Dey 1984). 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 interquark force or an instanton - like four fermion interaction (Rajagopal and Wilczek 2000).

For colour symmetric state (6) $\lambda_i, \lambda_j = \frac{1}{6}$, colour antisymmetric (3) $\lambda_i, \lambda_j = -\frac{1}{3}$ and for spin symmetric state (triplet) $S_i, S_j = \frac{1}{2}$ (b) spin antisymmetric (singlet) $S_i, S_j = -\frac{1}{2}$.

The spin and colour factor gives for flavor symmetric state, either $\frac{1}{3} \times (\frac{-2}{3}) = -\frac{1}{2}$, or $(\frac{-2}{3}) \times \frac{1}{2} = -1$. So in both cases the potential is repulsive. And for flavor antisymmetric state, either $\frac{1}{6} \times \frac{1}{6} = \frac{1}{36}$, or $\frac{1}{6} \times \frac{1}{6} = 2$, showing the

| Stars           | 4U 1735  | Serpens X = 1 | K5 1731 | 4U 1636 | 4U 1820 | GX 3+1 | 4U 1254 |
|-----------------|----------|---------------|---------|---------|---------|--------|---------|
| Distances (kpc) | 9.2      | 8.4           | 7       | 5.9     | 7.6     | 4−6    | 13 ±3   |
| Duration (Hrs.) | ~7       | ~4            | ~12     | ≥ 1−3   | ~3      | 4.4−16.2 | 14 ±2 |
| Energy range (keV) | 2−28    | 2−28          | 2−28    | 1.5−12  | 2−60    | 1.5−12 | 2−28    |
| $L_{\text{Peak}}$ (10^{38} erg s^{-1}) | 1.05 ± 0.1 | 1.6 ± 0.2 | 1.4 ± 0.1 | ~1.2 | 3.4 ± 0.1 | ~0.5 | .44 ± 0.2 |
| $E_{\text{b}}$ (10^{42} ergs) | ~0.5     | ~0.8          | ~1.0    | ~0.5−1.0 | ≥ 1.4  | ~0.5−2.0 | 0.8 ± 0.2 |
| $L_{\text{per}}$ (L_{\odot}) | ~0.25    | ~0.2          | ~0.1    | ~0.1   | ~0.1   | ~0.2   | ~0.13   |
| $kT_{\text{max}}$ (keV) | ~2.6 ± 0.2 | ~2.6 ± 0.2 | ~2.4 ± 0.1 | ~3.0 | ~1.0−2.0 | 1.8 ± 0.1 |
| $\tau_{\text{exp}}$ (Hrs.) | 1.4 ± 0.1 | 1.2 ± 0.1 | 2.7 ± 0.1 | 1.5 ± 0.1 | ~1.0 | ~1.6 | 6 ± 0.3 |
| $\alpha$        | 4400     | 5800          | 780     | 440     | 2200    | 2100   | 4800    |
potential to be attractive.

The expectation value of the potential (Eq. (11)) is taken between two two-body free particle wave functions $|ij>$ given by

$$|ij> = \frac{e^{-ik_r}\rho e^{-ik_r}}{\sqrt{\Omega}} = \frac{1}{\Omega} e^{-ik_r} e^{-ik_r}$$

(2)

where $\Omega = \frac{2}{\rho}$ is the total volume, $N$ being the total number of quarks and $\rho$ the total quark number density. Now

$$e^{-ik_r} e^{-ik_r} = e^{-ik_r} e^{-ik_r}$$

(3)

with $\mathbf{R}$ and $\mathbf{r}$ the centre of mass and relative coordinates with appropriate momentum conjugates $\mathbf{P} = \mathbf{k}_r + \mathbf{k}_i$ and $\mathbf{k} = (\mathbf{k}_r - \mathbf{k}_i)/2$. The energy expectation value is

$$<ij|H_{ij}|ij> = -(\lambda,\lambda_j)(S_i, S_j) \frac{2\alpha_s\sigma^2}{3m_m j_1^2}$$

$$\frac{1}{\Omega^2} \left( e^{ik_r e^{i\mathbf{R}}} \right) e^{i\sigma^2} e^{-ik_r e^{-i\mathbf{R}}}$$

(4)

Integrating over volume this reduces to

$$<ij|H_{ij}|ij> = -(\lambda,\lambda_j)(S_i, S_j) \frac{2\alpha_s\sigma^2}{3m_m j_1^2} f(k)$$

(5)

where $f(k) = (1-e^{i\sigma^2}/k^2)^2$ and $k^2 = \frac{1}{4}(k_x^2 + k_y^2 - 2k_xk_y \cos(\theta))$, $\theta$ being the angle between $\mathbf{k}_r$ and $\mathbf{k}_i$.

For each pair in particle the energy lowering due to one pair can be taken as

$$E_p(k) = \frac{1}{2} <ij|H_{ij}|ij>$$

$$= \frac{1}{2}(\lambda,\lambda_j)(S_i, S_j) \frac{2\alpha_s\sigma^2}{3m_m j_1^2} f(k).$$

(6)

If we consider one $u$ quark, then the lowering in energy of the $u$ quark will be due to all pair it can form with all $d$ quarks in the particular spin colour channel for which lowering is maximum that is spin-singlet and colour antisymmetric channel. So total lowering of energy of one $u$ quark with momentum $k_u$ is

$$E_u(k_u) = \frac{\Omega}{(2\pi)^3} \int E_p(k_u, k_d) d^3k_d.$$  

(7)

Then average energy lowering of $u$ quark is

$$\bar{E}_u = \frac{\int E_u(k_u) d^3k_u}{N_u}$$

$$= \frac{1}{2}(\lambda,\lambda_j)(S_i, S_j) \frac{2\alpha_s\sigma^2}{3m_m j_1^2} \cdot \frac{6 \times 2}{(2\pi)^2} I.$$  

(8)

where

$$I = \int_0^{k_f} \int_0^{k_f} \int_0^{k_f} f(k_{ud}, k_d, \theta) d k_{ud} d k_d d \theta$$

(9)

Similarly,

$$\bar{E}_d = \frac{1}{2}(\lambda,\lambda_j)(S_i, S_j) \frac{2\alpha_s\sigma^2}{3m_m j_1^2} \cdot \frac{6 \times 2}{(2\pi)^2} I.$$  

(10)

Hence lowering of one $ud$ pair is

$$\bar{E} = \bar{E_u} + \bar{E_d}$$

$$= \frac{-1}{2}(\lambda,\lambda_j)(S_i, S_j) \frac{2\alpha_s\sigma^2}{3m_m j_1^2} \cdot \frac{6 \times 2}{(2\pi)^2} I.$$  

Integrating Eq. (2) in the range from 0 to $k_f$ of respective quarks the contribution of a $ud$ diquark in the energy has been shown in the Table 4 for three different EOSs given by Dey et al. (1998) and for the two possible colour-spin channels with appropriate parameters $\sigma$ and $\alpha_s$.

The Table 4 shows that the variation of the correlation energy is significant, when different sets for the smearing in the spin-spin potential are chosen. The variation with the EOSs is comparatively unimportant. We re-emphasize that the maximum numbers in this table ~ 50 MeV are close to the energy obtained from conversion of normal accreted matter to strange matter, if any, and could thus provide the energy needed for reaching a high temperature as in carbon burning scenario.

3. OBSERVATION AND CONCLUSION

It is seen from the Table 4 the lowering in energy per pair due to spin-spin interaction varies and is larger for the singlet channel where it may be 58 MeV whereas in the triplet channel it is less than 10. When a Type I burst occurs both channels may be excited equally and some 30 MeV may be absorbed for an average pair breaking.

The number density of quarks on the surface of the strange star is ~ 0.27 f m$^{-3}$. With this number density the re-alignment of quarks within a depth of a few micron will liberate a total energy of the order of 10$^{53}$ MeV.

After a type I burst the broken pairs are converted to diquarks and there will be an energy release which will couple to the gravitational energy of the accreted particles and this will lead to a large alpha between bursts.

The scenario for superbursts from strange stars is that a micron-thick layer of diquarks, at the star surface, get broken due to repeated Type I bursts during high accretion. Some of the broken pairs form diquarks again - thus supplementing the energy released during accretion between bursts - and producing a large value of $\alpha$. When the number of broken pairs and diquarks reach a critical balance, the transition is expected to go like an avalanche. This is due to the two-fermion to boson transformation where the number of bosons enhance a transition. For this phenomenon to take place the accretion must be high. And for GX 17+2 - where the accretion is near the Ed-dington limit - one would naturally expect recurring superbursts with short intervals between them as is indeed observed. After the superbursts, the reverse process takes over during the subsequent normal bursts, if any. The crucial fact is that the recombination time scale is long, since the strong interaction pairing is supplemented by beta equilibrium and charge neutralization which are slower weak electromagnetic process. The least observed time interval between two superbursts is 8.2 days which is 100 times the burst period of about 2 hours. The ratio is like the ratio of strong to electromagnetic interaction, showing that pair breaking takes that much more time, as expected. The values of $\alpha$ find a natural explanation in the enhanced gravitational
Table 2

INTEGRATED VALUES FOR THE PAIRING ENERGY EQ. (1) FOR DIFFERENT PAIRS FOR SPIN SINGLET (COLOUR 3) STATES IN MeV. FOR SPIN TRIPLET (COLOUR 6) STATE THE ENERGIES IS SIX TIMES LESS.

| Colour-spin states | Sets | \( \alpha_s \) | \( \sigma \) | EOS |
|--------------------|------|---------------|------------|-----|
|                    |      | fm\(^{-1}\)   |            |     |
| spin singlet       | 1    | 0.5           | 6.0        | -23.578 | -23.744 | -25.901 |
|                    | 2    | 0.5           | 4.56       | -23.287 | -23.451 | -25.561 |
| and colour \( \bar{3} \) | 3    | 0.87          | 6.0        | -41.125 | -41.316 | -45.067 |
|                    | 4    | 0.87          | 2.61       | -38.225 | -38.484 | -41.807 |
|                    | 5    | 1.12          | 6.0        | -52.814 | -53.188 | -58.018 |
|                    | 6    | 1.12          | 2.03       | -46.636 | -46.941 | -50.847 |
| spin triplet       | 1    | 0.5           | 6.0        | -3.930  | -3.957  | -4.317  |
|                    | 2    | 0.5           | 4.56       | -3.881  | -3.908  | -4.260  |
| and colour 6       | 3    | 0.87          | 6.0        | -6.837  | -6.868  | -7.511  |
|                    | 4    | 0.87          | 2.61       | -6.371  | -6.414  | -6.968  |
|                    | 5    | 1.12          | 6.0        | -8.802  | -8.865  | -9.670  |
|                    | 6    | 1.12          | 2.03       | -7.773  | -7.823  | -8.474  |

Field of the strange star and in the energy released due to pairing of diquarks broken up during a Type I burst.

We expect that when alpha is large it will signify most of the broken pairs have changed into diquarks. When alpha is not so large superburst recurrence is perhaps more likely and we find this in the case of 4\( ^{16} \)\( ^{36} \)U where alpha is only 440 and three superbursts have already been spotted.

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