Kilohertz QPOs and strange stars

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ABSTRACT The kilohertz quasi periodic oscillations (QPOs) discovered in several low mass X-ray binaries (LMXBs) by the Rossi X-ray Timing Explorer (XTE) are thought to occur at the orbital frequency in accretion discs whose inner edge corresponds to the innermost (marginally) stable orbit allowed by general relativity. These ideas have been applied to constrain the equation of state (e.o.s.) of the central neutron star. Here we discuss another possibility, that the central object is a strange star, and show how kHz QPOs constrain the e.o.s. of strange matter.

KEYWORDS: stars: strange, X-rays: general

1. INTRODUCTION

As first suggested by Bodmer (1971), bulk matter in its stable form may be composed of deconfined up, down and strange quarks. This implies a possible existence of strange stars - compact objects consisting of such quark matter (Witten 1984). Glitching radio-pulsars are neutron stars and not strange stars (Alpar 1987), and since their formation would be precluded in a Galaxy contaminated by the disruption of a strange star in a binary merger (Madsen 1988, Caldwell and Friedman 1991), it has been suggested that strange stars cannot be formed directly in supernovae but could exist as millisecond pulsars (Klużniak 1994) and be formed in LMXBs in an accretion-triggered phase transition of neutron-star matter to strange matter (Cheng and Dai 1996). This phase transition could be accompanied by a gamma-ray burst (ibid.).

The launch of the XTE brought the discovery of high frequency QPOs in the X-ray flux of bright Galactic sources (van der Klis et al. 1996, Strohmayer et al. 1996). Kilohertz QPOs have now been found in about a dozen LMXBs. The QPOs often come in frequency pairs, with the difference between the two frequencies roughly constant for most objects. In some sources, for example in 4U 1728-34 (Strohmayer et al. 1996), a third QPO frequency equal to the difference between the two higher frequencies, or its second harmonic, is observed during X-ray bursts. The usual interpretation of these phenomena is that the third frequency is the spin frequency of the star, whose beat with the highest frequency QPO gives rise to the lower frequency of the “kHz” QPO pair. However, in some sources the difference is not constant, e.g. in Sco X-1 (van der Klis et al. 1996) and in 4U1608-52 (Méndez et al. 1998), so the interpretation of the lower frequency QPOs is uncertain.
The X-ray flux of accreting degenerate stars may be modulated at the orbital frequency (Bath 1973, Boyle, Fabian and Guilbert 1986) and it has been expected that in the general-relativistic “gap” regime (Kluźniak and Wagoner 1985)—in which the neutron star is inside the marginally stable orbit, so the accretion disk cannot extend to the stellar surface—clumps in the inner accretion disk may give rise to modulations of flux in the kHz range with a characteristic maximum frequency close to the orbital frequency in the marginaly stable orbit (Kluźniak et al. 1990). There is no theory of QPOs, but in keeping with this tradition we will identify the highest QPO frequency with orbital frequency in the accretion disk.

In this work we assume that the compact objects in LMXBs are strange stars and discuss the implications of the kilohertz QPOs on the properties of strange matter. As we show below, the stringest lower limit on the density of bulk strange matter corresponds to the highest orbital frequency. The highest QPO frequency so far has been observed in 4U 1636-53 at 1230 Hz (Zhang et al. 1997a).

2. STRANGE MATTER EQUATION OF STATE

We describe strange matter by a stiff, but still causal, equation of state:

\[ P(\rho) = (\rho - \rho_0) c^2 / 3, \quad (1) \]

where \( \rho_0 \equiv \rho_{14} \times 10^{14} \text{g/cm}^3 \) is the density of bulk strange matter. To determine the stellar mass-radius relation plotted in Fig. 1, we solve the Oppenheimer-Volkoff equation (e.g. Shapiro and Teukolsky 1983). We note that the mass and radius of the star satisfy the scaling relations (Witten 1984, Haensel et al. 1986):

\[ M(\rho')/M(\rho_0) = (\rho_0/\rho')^{1/2}, \quad R(\rho')/R(\rho_0) = (\rho_0/\rho')^{1/2} \quad (2) \]

In the presence of a crust the relations (2) are approximate, however in the limit of large masses (close to the maximal mass) they do hold.

3. LIMITS ON \( \rho_0 \).

**Lower limit.** Suppose that the highest QPO frequency observed, 1230 Hz, is a keplerian frequency. The lines of constant keplerian frequency, \( f \), in a mass–radius diagram are described by

\[ R = (2\pi f)^{-2/3} (GM)^{1/3}. \quad (3) \]

They terminate at the radius of the marginally stable orbit, \( R = r_{ms} = 6GM/c^2 \). Since the star must fit inside the keplerian orbit, the curve describing the stellar mass radius relation must intersect, or at least be tangent to, the wedge-shaped region bounded from above by the line corresponding to the given keplerian frequency and by the marginally stable orbit line from below. This is shown in Figure 1, from which we see that the observed frequency of 1230 Hz implies a lower limit on the density of \( \rho_0 > 1.71 \times 10^{14} \text{g/cm}^3 \).
FIGURE 1. The mass radius diagram for non-rotating stars. Keplerian orbits are allowed in the region for which \( R \geq 6M \). The upper thick line corresponds to the Keplerian frequency of 1230 Hz. Mass radius relations for strange stars, corresponding to the limiting cases described in the text, are also shown.

Upper limit. In order to find also an upper limit on the density parameter, \( \rho_0 \), we make the additional assumption that the maximum QPO frequency in a given source corresponds to orbital motion in the marginally stable orbit (Kaaret et al. 1997, Kluzniak 1997, Zhang et al. 1997b). This leads automatically to the determination of the mass (for a non-rotating star):

\[
M = 2.20M_\odot \times \frac{1.00\text{kHz}}{f}.
\]  

(4)

Inserting \( f = 1230 \) Hz, we find that the mass of the central object is \( M = 1.78M_\odot \). This yields an upper limit on the strange matter density of \( \rho_0 < 5.15 \times 10^{14} \text{g/cm}^3 \). A more stringent upper bound is obtained by considering a lower frequency. There is strong evidence that the QPO frequency saturates at the value \( f = 1060 \) Hz in the LMXB 4U 1820-30 (Zhang et al. 1998). Inserting this value of \( f \) in eq. (4) we obtain \( M = 2.08M_\odot \). Eq. (2) then implies that the upper bound on the density parameter decreases by the factor \((1060/1230)^2 = 0.743 \), yielding \( \rho_0 < 3.82 \times 10^{14} \text{g/cm}^3 \). For stars with moderate angular momentum \( J \), the mass is increased by a factor \( 1 + 0.75cJ/(GM^2) \) (Kluźniak et al. 1990), but deriving a limit on \( \rho_0 \) would require construction of fully relativistic models of rotating strange stars.
4. DISCUSSION

We have shown that the existence of kilohertz QPOs leads to constraints on the bulk strange matter density. For a slowly rotating star (with angular momentum $J \ll GM^2/c$) we find $1.7 \times 10^{14} \text{g/cm}^3 < \rho_0 < 3.8 \times 10^{14} \text{g/cm}^3$. The only assumption used to obtain the lower limit is that the maximum QPO frequency observed in LMXBs corresponds to keplerian motion around a slowly rotating strange star. To obtain the upper limit we assumed that the highest observed QPO frequency in 4U 1820-30 corresponds to the orbital frequency in the marginally stable orbit. These limits can be improved by continued observations of LMXBs, which may result in detection of higher QPO frequencies in some sources and lower in others. The current upper limit already rules out simplest models for the putative strange star in 4U 1820-30, as the physical limits in a bag model with massless non-interacting quarks are $4.2 < \rho_{14} < 6.5$ (Haensel, private communication).

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