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LETTER

Letter to the Editor

Do LMXBs contain strange stars?

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Abstract. It has been suggested that low mass X-ray binaries (LMXBs) contain strange (quark) stars. We show that the properties of bulk strange matter are severely constrained if the recently discovered kilohertz quasi periodic oscillations (QPOs) of the X-ray flux from LMXBs occur at orbital frequencies around strange stars. In particular, the simplest equation of state of strange matter is ruled out if the observed saturation (at 1.07 kHz) of the QPO frequency in 4U 1820−30 occurs at the orbital frequency either just outside the surface of the strange star or in the innermost (marginally) stable orbit allowed by general relativity.

Key words: dense matter – equation of state – stars: binaries: general – X-rays: stars

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 young 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, it has been suggested that strange stars cannot be formed directly in supernovae (Madsen, 1988; Caldwell & Friedman, 1991), but could exist as millisecond pulsars (Kluźniak, 1994) and be formed in LMXBs in an accretion-triggered phase transition of neutron-star matter to strange matter, which could be accompanied by a gamma-ray burst (Cheng & Dai, 1996).

In this letter we assume that the compact objects in LMXBs are strange stars and discuss the resulting implications of the recently discovered kilohertz QPOs for the theory of dense matter. We show that with the standard keplerian interpretation of kHz QPOs, the sources cannot be strange stars modeled with a simple equation of state (Eq. [1]). Future work will show whether this necessarily means that LMXBs do not contain strange stars or whether more sophisticated equations of state of strange matter may still be viable.

2. Interpretation of kilohertz QPOs

High frequency QPOs in the X-ray flux of bright Galactic sources were discovered (van der Klis et al., 1996a; Strohmayer et al., 1996a) after the launch of the Rossi X-ray Timing Explorer (XTE). 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, even as the two QPO frequencies vary with time over a range of several hundred hertz each. In some sources, for example in 4U 1728−34 (Strohmayer et al., 1996b), 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 follows Patterson's model for the QPO frequency in AE Aquarii (Patterson 1979): the third frequency is the spin frequency of the star, whose beat with the orbital frequency gives rise to the lower frequency of the "kHz" QPO pair. In fact the difference between the two frequencies in the QPO pair is not always constant, e.g. it is not in Sco X-1 (van der Klis et al., 1996b) and in 4U1608−52 (Mendez et al., 1998), so the interpretation of the lower frequency QPOs is uncertain. However, here we are only interested in the highest frequency.

Our main assumption is that the highest frequency QPO peak occurs at an orbital frequency about the central star. The idea that the X-ray flux of accreting degenerate stars may be modulated at the orbital frequency goes back to Bath (1973), Patterson (1979) and Boyle et al. (1986). Also, it had been specifically suggested that in LMXBs orbital modulation may be observed in the kilohertz range (Kluźniak et al., 1990). Thus our basic assumption is in keeping with tradition, it also agrees with other authors' interpretation of kHz QPOs (compare Strohmyer et al. 1996b, Kaaret et al. 1997, Kluźniak 1998, Zhang et al. 1997b, Thampan et al. 1999). Further, the orbital nature of the flux modulation in kHz QPOs would be consistent with the observed saturation of the QPO frequency in 4U 1820−30 (Zhang 1998). Indeed, in sufficiently weakly magnetized compact stars orbital frequency is expected to reach a maximum just outside the stellar surface (Shakura 1972) if qualitative effects of general relativity can be ignored, or a maximum close to the frequency of the marginally stable orbit (Kluźniak et al., 1990), if the star is sufficiently compact that general relativistic effects become qualitatively important (Kluźniak & Wagoner, 1985).

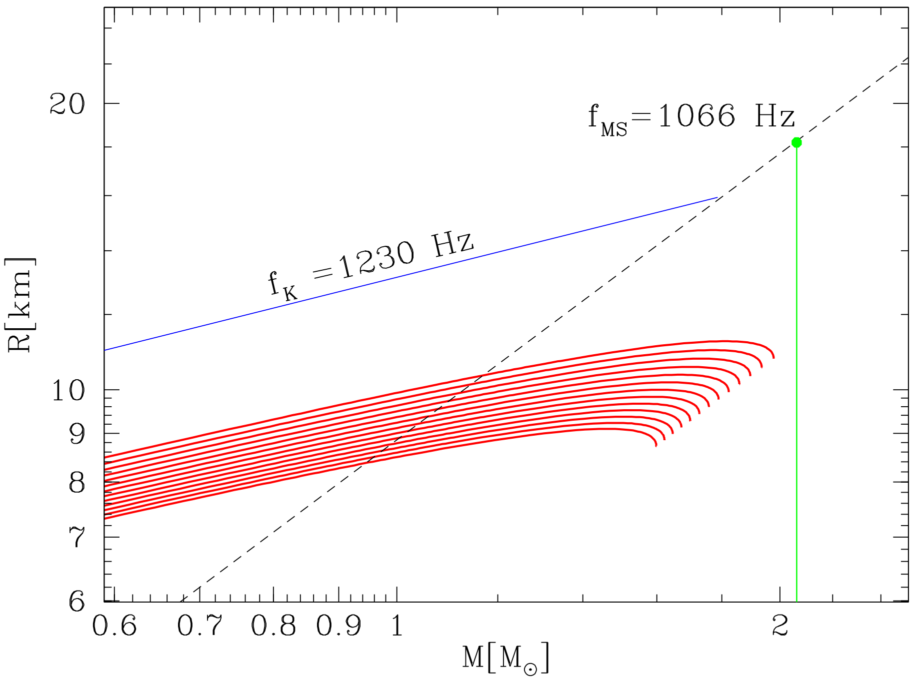

Fig. 1. The mass–radius diagram for non-rotating stars. We show a series of thirteen possible mass–radius relations for strange stars, spanning the allowed range $4.2 < \rho_{14} < 6.5$. Two data values are presented: (a) the line corresponding to the keplerian frequency of 1230 Hz, and (b) the point corresponding to the marginally stable orbit at 1066 Hz. All mass–radius relations are consistent with the constraint (a), however none can satisfy (b).

3. Strange matter equation of state

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

$$P(\rho) = (\rho - \rho_0)\, c^2/3\,, \tag{1}$$

where $\rho_0 \equiv \rho_{14} \times 10^{14}\,\mathrm{g/cm^3}$ is the density of bulk strange matter. To determine the radius as a function of the stellar mass 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):

$$M(\rho_0')/M(\rho_0) = (\rho_0/\rho_0')^{1/2}\,, \tag{2}$$

$$R(\rho_0')/R(\rho_0) = (\rho_0/\rho_0')^{1/2}\,. \tag{3}$$

These scaling relations are reminiscent of those for a relativistic star of a uniform density ρ_0 (Schwarzschild 1916). For strange stars, relations (2), (3) are approximate in the presence of a crust, however in the limit of large masses (close to the maximal mass) they do hold accurately. The physical limits on the density parameter in a bag model with massless non-interacting quarks are $4.2 < \rho_{14} < 6.5$ (Haensel, private communication). In Fig. 1 we show a family of mass–radius relations for static strange stars with the value of ρ_0 in this range. Note that for this family, the maximum allowed mass is $M_{\rm max} = 1.98 M_\odot$ (attained for $\rho_{14} = 4.2$). We will compare this value with the empirical limits on the mass derived from the QPO frequency.

4. Observational constraints

The idea of measuring the mass of an object by observing the orbital period of a body revolving about the object at a known distance dates back to Newton (1687). We will use two periods, one corresponds to the highest frequency observed—so far this is 1230 Hz in 4U 1636−53 (Zhang et al., 1997a)—the other is the saturation frequency in 4U 1820−30, i.e. 1066 Hz (Zhang et al., 1998). Even more stringent limits would be obtained by using the lowest of the likely maximum QPO frequencies, 1020 Hz, observed in Cyg X-2 (Wijnands et al., 1998), however in this case the evidence that the maximum value observed to date is indeed the highest attainable QPO frequency in the system is not as convincing as in the case of 4U 1820−30.
The lines of constant keplerian frequency, f, in a mass–radius diagram are described by

$$R = (2\pi f)^{-2/3}\,(GM)^{1/3}\,. \tag{4}$$

They terminate at the radius of the marginally stable orbit, $R = r_{\rm ms} = 6GM/c^2$. Since the star must fit inside the keplerian orbit, the curve describing the stellar mass radius relation must at least in part lie below the line described by equation (4). This is shown in Fig. 1, from which we see that the maximum observed frequency of 1230 Hz is fully consistent with all of the possible "physical" strange star mass–radius relations—an orbital frequency of 1230 Hz implies a lower limit on the density of $\rho_0 > 1.71 \times 10^{14}$ g/cm^3, which agrees well with the physical limits. But if we consider the saturation frequency as well, the constraints become more stringent.

First assume that the QPO frequency in 4U 1820−30 saturates because the orbit is just outside the stellar surface. Then, ρ_0 must be such that the mass–radius curve crosses the line of $f = 1066$ Hz (Fig. 2). This requires $1.31 < \rho_{14} < 1.60$, a range incompatible with the limit $\rho_{14} > 1.71$, just derived from the orbital frequency of 1230 Hz. In other words, if there exists a strange star with orbital frequency of 1066 Hz at its surface, then no strange star can allow orbital frequency of 1230 Hz, regardless of the value of ρ_0. Here, a "strange star" means "a static star modeled in general relativity with the equation of state (1)".

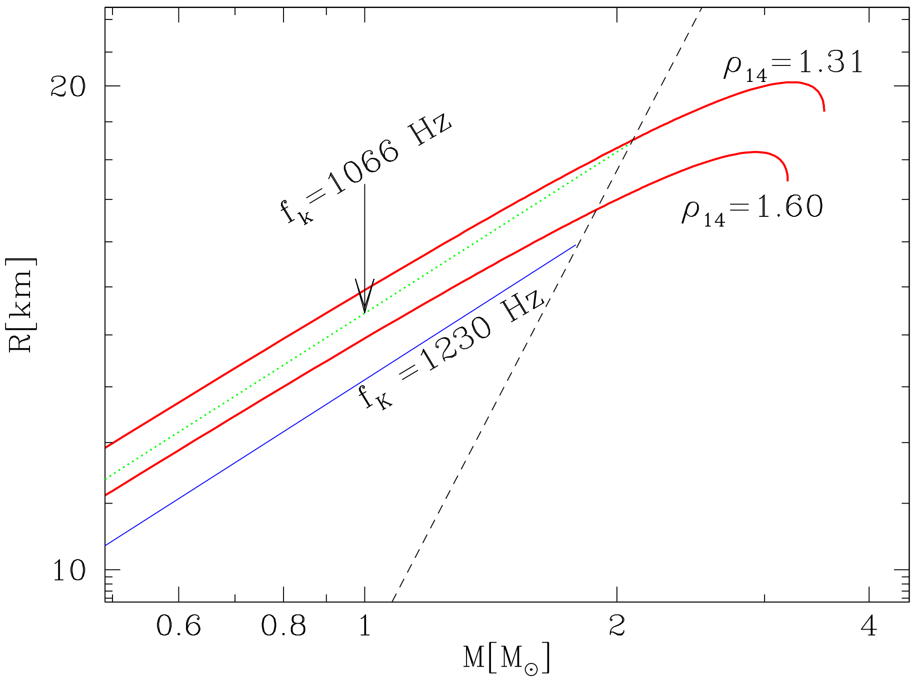

Fig. 2. If 1066 Hz is an orbital frequency just above the surface of a strange star, the mass–radius curves of the star (modeled with the e.o.s. [1]) must lie between the two thick curves labelled "$\rho_{14} = 1.31$" and "$\rho_{14} = 1.60$." A circular orbit of frequency 1230 Hz would then never be outside the stellar surface, as it would have a smaller radius (straight line segment labelled "$f_K = 1230$ Hz"). The dashed line indicates the radius of the marginally stable orbit.

Suppose instead, that the saturation frequency is an orbital frequency at the marginally stable orbit. This leads directly to the determination of the stellar mass for a non-rotating star (Kluźniak et al., 1990; Kaaret et al., 1997; Zhang et al., 1997b):

$$M = 2.20 M_\odot \times (1.00\,\mathrm{kHz}/f)\,. \tag{5}$$

For $f = 1066$ Hz we obtain $M = 2.08 M_\odot$, which is more than the maximum allowed mass of the family of models described at the end of Sect. 3 (see Fig. [1]). In other words, under this interpretation of data, the upper bound on the density parameter is $\rho_0 < 3.82\times10^{14}$ g/cm^3. This is an upper limit *below* the lowest physically allowed $\rho_0 = 4.2 \times 10^{14}$ g/cm^3. Thus, with this interpretation of the maximum frequency of 1066 Hz (Zhang et al., 1998), the compact star in 4U 1820−30 cannot be modeled with the strange matter e.o.s. of Eq. (1) for any value of the bulk viscosity parameter in the physical range $4.2 < \rho_{14} < 6.5$.

For stars with moderate angular momentum J, Eq. (5) takes the form (Kluźniak et al., 1990).

$$M = 2.20 M_\odot \left(1 + 0.75 \frac{cJ}{GM^2}\right) \times \frac{1.00\mathrm{kHz}}{f}\,. \tag{6}$$

Thus, for a rotating strange star the maximal mass implied by the observed frequency is even larger than for the case of a non-rotating star. Of course the mass–radius relation for a rotating strange star will also be different, but to lowest order rotation increases the radius for a given mass. Therefore, to first order in J/M^2, the constraint from the marginally stable orbit frequency (vertical line) moves to the right in Fig. 1 with increasing stellar angular momentum, while the curves describing the mass–radius relations will move up. Exact treatment of this problem requires construction of fully relativistic models of rotating strange stars.

5. Conclusions

In discussing the implications of the observed kilohertz QPOs for the hypothesis that LMXBs contain strange stars, we made the following assumptions: (a) the highest frequency QPO is a Keplerian frequency in Schwarzschild metric, (b) when the highest QPO frequency saturates with the count rate it does so at the orbital frequency either at the stellar surface or in the marginally stable orbit, (c) the compact star in 4U 1820−30 is slowly rotating, i.e. $J \ll GM^2/c$, (d) the stars can be modeled with the e.o.s. of Eq. (1). The currently observed QPOs already rule out this simplest model [(c), (d)] for the putative strange stars in LMXBs, because under these assumptions the properties of kilohertz QPOs in 4U 1820−30 and 4U 1636−53 severely constrain the bulk strange matter density. We find 1.7×10^{14} g/cm^3 $< \rho_0 < 3.8\times10^{14}$ g/cm^3, while the physical limits in a bag model with massless non-interacting quarks are 4.2×10^{14} g/cm$^3 < \rho_0 < 6.5 \times 10^{14}$ g/cm^3.

Definitive conclusions regarding the presence of strange stars in low-mass X-ray binaries require studying a broader range of strange matter equations of state, as well as constructing models of rotating strange stars.

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