QUARK STARS IN LOW-MASS X-RAY BINARIES: FOR AND AGAINST

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ABSTRACT

It has been suggested that both X-ray bursters and millisecond radio pulsars may be strange (quark) stars, rather than neutron stars. Confirming (or rejecting) this suggestion may require knowing what role strong-field effects of general relativity play in the accretion flow of the compact X-ray source in low-mass X-ray binaries (LMXBs). We discuss the range of rotational and orbital frequencies, and of masses expected in various models of strange stars, and compare them with observational constraints, suggested by the observed frequencies of kHz QPOs. We explain why future observations of transients (such as SAX J 1808.4-3658) may be crucial to understanding the precise nature of the accreting source. For flattened (e.g., rapidly rotating) distributions of matter, an innermost (marginally) stable orbit may be present even if relativistic effects are negligible. Depending on the stellar rotation rate, the same value of orbital frequency in the innermost stable orbit (say, 0.9 kHz) can correspond to a star of mass equal to $2.4M_\odot$, $1.4M_\odot$, $0.1M_\odot$, $0.01M_\odot$, or less.

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

1. INTRODUCTION

Bodmer (1971) suggested that quark matter (composed of roughly equal number of up, down, and strange quarks) is the ground state of matter. Brecher and Caporaso (1976), Witten (1984), Alcock et al. (1986), Haensel et al. (1986), and others, have computed the structure of gravitating objects composed of such matter, the so called strange stars. Because the density of quark matter would exceed only slightly nuclear density, the radii of these quark stars would be comparable to the radii of neutron stars, as would be the maximum masses—it would be hard to distinguish the two at first sight. Although young glitching radiopulsars are likely to be neutron stars (Alpar 1987), we are unaware of any reason why either the observed millisecond pulsars, or X-ray bursters (as well as the “Z sources”) in LMXBs, should not be quark stars instead.

Unlike for neutron stars, which can exist only above a certain mass ($\sim 0.1M_\odot$), there is no lower limit to the mass of a strange star, so the discovery of a star with a minute radius, less than about 5 km, or of a heavy planet of an enormous density, would immediately confirm the existence of quark matter. An unusually high rotation rate could also reveal a quark star.

A precise determination of the mass is in principle possible through the measurement of the orbital period in an accretion disk (as in the supermassive black hole candidate NGC4258, where the velocity of water masers at various distances from the central object has been measured: Miyoshi et al., 1995). In LMXBs, it is currently not feasible to resolve spatially any “blobs” orbiting in the disk; however, the mass of the compact star can be determined from the maximum orbital frequency, $f_{\text{orb}, \text{max}}$, on the assumption that this maximum is attained in the marginally stable orbit of general relativity (Kluzniak et al. 1990). The recently discovered kHz QPOs can in principle be used to determine the orbital frequencies. In the simplest model the QPO frequencies are the orbital frequencies and, on the assumption just stated, the mass of the compact star in some sources can be thus determined (e.g. Kaaret et al. 1997, Zhang et al. 1998, Kluzniak 1998, Bulik et al. 1999b). Such considerations make important determining the range of possible orbital periods for various models of quark stars (Stergioulas et al. 1999; Zdunik et al 2000a,b) and of neutron stars (Thampan et al. 1999).

Here, we summarize our studies of quark star masses and frequencies (rotational and orbital), and point out a new complication: the marginally stable orbit exists also in Newtonian gravity! If higher mass multipoles are present in the distribution of matter, estimates of the central mass from the maximum orbital frequency alone are unreliable. As we show, the same value of $f_{\text{orb}, \text{max}}$ can correspond to two stars differing in mass by a factor of a hundred, or more. It is crucial to know the rotational period of a quark star, if its mass is to be even approximately determined from the orbital frequency.
2. TWO MODELS OF QUARK MATTER AND OF STRANGE STARS

Traditionally, strange stars were modeled with an equation of state based on the MIT-bag model of quark matter (Farhi and Jaffe 1984), in which quark confinement is described by an energy term proportional to the volume. Recently, Dey et al. (1998) proposed a model in which quark interactions and confinement are described in a more self-consistent manner. In fact, both models give a simple equation of state

\[ P = a(\rho - \rho_0)c^2, \tag{1} \]

where \( a \) is a constant of model-dependent value (close to, but generally not equal to, 1/3 for the MIT-bag model, Zdunik 2000). It is the value, \( \rho_0 \), of density at zero pressure which is crucial for various limiting properties of strange stars; e.g., the maximum mass of static strange stars is \( M = 2M_\odot(\rho_0/4 \times 10^{14})^{-1/2} \) in the MIT-bag model (Witten 1984), and the scaling of mass with \( \rho_0^{-1/2} \) is general.

Below, we describe our main results obtained for MIT-bag model stars. For other models of quark stars the results are qualitatively similar, However, in general the Dey et al. (1998) model gives more compact stars, with lower maximum mass and lower radii than the MIT-bag model stars. This also translates to higher possible rotational and orbital frequencies for the “Dey stars” (Gondek-Rosińska et al. 2000a,b).

3. SUMMARY OF RESULTS

We were mostly interested in the value of maximum orbital frequency of test particles (or fluid elements in an accretion disk) around such stars. A very specific question was asked (Bulik et al. 1999a,b) whether the observed maximum frequency of kHz QPOs in 4U 1820-30, 1.07 kHz, is compatible with strange star models—for static stars such a frequency is obtained in the marginally stable orbit only for the relatively high mass of nearly \( 2M_\odot \), according to the formula for the maximum orbital frequency in Schwarzschild metric, \( f_{\text{orb}} = 2198 \text{kHz} (M_\odot/M) \). We found, that with the current physical constraints on \( \rho_0 \) (eq. [1]) masses of static strange stars as high as \( 2.4M_\odot \) cannot be ruled out (Zdunik et al. 2000a).

To gauge the range of allowed orbital frequency, Stergioulas et al. (1999) computed models of maximally rotating quark stars. The main results are, that for these models the innermost (marginally) stable circular orbit (ISCO) is always well above the stellar surface (even though rapid rotation leads to a large increase of the equatorial radius), and that the ISCO frequencies are usually much lower for rapidly rotating stars than for static ones, with a value as low as 950 Hz for a 1.4\( M_\odot \) star rotating at the equatorial mass shedding limit. Only close to the maximum mass do ISCO frequencies in maximally rotating stars come close to the kHz range.
ing quark stars become comparable to the static values. However, the ratio $T/W$ in these stars exceeds the Newtonian limit for instability ($T/W > 0.1375$), so probably these extreme configurations cannot exist. Detailed models of quark stars rotating at all possible rates can be found in Zdunik et al. 2000b.

The gap between the ISCO and the stellar surface is always present for quark stars more massive than $1.4$ to $1.6M_\odot$ (depending on the model). At somewhat lower masses the gap disappears for moderate rotation rates (but the marginally stable orbit is present for both slowly and rapidly rotating stars of this mass). It is only for the lowest mass stars, that the gap disappears even at zero rotation rate.

4. THE LOW MASS LIMIT

The limit $M \to 0$ corresponds to $\rho \to \rho_0$ in eq. (1), i.e., the star tends to a nearly uniform density configuration. At the same time, the dimensionless angular momentum parameter $j = cJ/(GM^2) \to \infty$, so an expansion in powers of angular momentum (Kluźniak and Wagoner 1985, Shibata and Sasaki 1998) is impossible; however, the limit is, in fact, Newtonian. In Fig. 1 we show the maximum value of orbital frequency, as a function of stellar rotation rate, for a low mass quark star (the curve is nearly universal for all $M < 0.1M_\odot$). The computation was carried out with a fully relativistic code, described in Gourgoulhon et al. (1999).

For all periods of rotation larger than about 1.03 ms, there are stable circular orbits just outside the surface. For non-rotating stars, $f_{\text{orb}, \text{max}}$ is simply given by Kepler’s law, and its value decreases as the equatorial radius increases for rotating stars. The cusp in the curve at about 970 Hz corresponds to the appearance of a gap between the star and the ISCO. In this case, this is a purely Newtonian effect related to the flattening of the star at rapid rotation rates (see also Zdunik and Gourgoulhon 2000).

To demonstrate the existence of marginally stable orbits in Newtonian theory, we present in Fig. 2 the angular momentum in circular orbit around a uniform density disk, computed from the Newtonian gravitational potential of this non-spherical mass distribution.

The conclusion is, that because of the appearance of the marginally stable orbit in Newtonian gravity (when octupole and higher mass multipoles are sufficiently large), the maximum orbital frequency can reach fairly low values even for extremely low-mass stars. Conversely, $f = 1.1$ kHz in the marginally stable orbit need not imply that $M = 2M_\odot$, we have exhibited a specific example where the mass is $< 0.01M_\odot$, instead.

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