INNERMOST STABLE CIRCULAR ORBITS AROUND ROTATING COMPACT QUARK STARS AND QPOS

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ABSTRACT

It has been suggested that observations of quasi periodic oscillations (QPOs) in the X-ray fluxes from low mass X-ray binaries can be used to constrain the mass of the compact object and the equation of state of its matter. A specific suggestion that the kHz QPO frequency saturates at the maximum orbital frequency has been widely considered. We examine rotating compact stars described by a new model of strange quark matter (Dey et al. 1998). We calculate the maximum orbital frequencies for both normal and supramassive strange stars described by the Dey et al. model, and present these frequencies for sequences of equilibrium models with constant baryon mass. The maximum orbital frequencies for these compact objects are always higher than the kHz QPO frequencies observed to date.

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

1. INTRODUCTION

The recently discovered kHz QPOs can be used as a probe of the inner regions of accretion disks in compact stars and hence also of the properties of the central object. These oscillations have been used to derive estimates of the mass of the neutron star in some sources (e.g. Kaaret et al. 1997, Zhang et al. 1998, Kluźniak 1998) and of strange stars given by the MIT bag model (Bulik et al. 1999, Stergioulas et al. 2000, Zdunik et al 2000a,b). All these estimates assume that the maximum observed frequency is the orbital frequency in the innermost marginally stable orbit, as suggested by Kluźniak et al. (1990).

Very recently, a new model of strange quark matter (Dey et al. 1998) was used for calculating frequencies of marginally stable orbits around static strange stars and strange stars rotating with frequency 200 Hz and 580 Hz (Datta et al. 2000). The authors conclude that very high QPO frequencies in the range of 1.9-3.1 kHz, if observed, would imply the existence of a compact strange star in the X-ray binary, rather than a neutron star. Two cases of the Dey model have been used in these papers. Both cases (differing in the value of a free parameter) give a rather low value for the maximum gravitational mass of static configurations $M_{\text{max}} = 1.32 M_\odot$ (with the stellar radius $R = 6.5$ km) and $M_{\text{max}} = 1.44 M_\odot$ ($R = 7.1$ km).

In the present paper we calculate the highest Keplerian frequencies of rotating quark stars, for two Dey models, for equilibrium sequences with fixed baryon mass. We perform calculations for all possible stellar rotation rates. We find the absolute upper limit on the orbital frequency. We show that the Dey models considered do not allow maximum frequencies which are lower than 1.5 kHz for stars with masses $M > 1 M_\odot$.

2. CALCULATIONS

We have calculated the innermost stable circular orbit of the uniformly rotating strange stars described by the Dey model using the multi-domain spectral methods developed by Bonazzola et al. (1998). This method has been used previously for calculating rapidly rotating strange stars described by the MIT bag model (Gourgoulhon et al. 1999) and for finding basic properties of rapidly rotating strange stars described by the Dey model (Gondek-Rosińska et al. 2000). The multi-domain technique allows one to address the density discontinuity at the surface of self-bound stars.

The Dey et al. model (in contrast to MIT bag model) describes quark confinement self-consistently. The mean density of the stars considered here is about $10^{15}$ g/cm$^3$. The stars are very compact—the gravitational redshifts $z$ for the maximum-mass static configurations are much larger than those of strange stars within the MIT bag model or of most models of neutron stars. Thus, Dey stars can rotate extremely fast. We perform calculations for equilibrium sequences with baryon masses from $0.5 M_\odot$
upwards. The maximal baryon mases are $1.64 \, M_\odot$ and $1.85 \, M_\odot$ for static Dey stars in the two cases considered (Gondek-Rosińska et al. 2000), but we include supramassive stars with baryon masses up to $2.2 \, M_\odot$ and $2.5 \, M_\odot$, respectively. The results for the two models are plotted in Fig. 1 and Fig. 2, respectively.

3. ORBITAL FREQUENCIES

We find that:

a) for stars with moderate and high baryon masses (higher than $\sim 60\%$ of the maximum baryon mass of static configurations) a gap always separates the innermost stable circular (ISCO) and the stellar surface, for any stellar rotation rate;

b) for low mass-stars with moderate rotation rates, stable orbits extend down to the stellar surface (see, e.g., in Fig 1. the parts between the cusps of the sequences with baryon masses 0.87 and 0.79$M_\odot$);

c) in the Dey model, as in the MIT bag model, for strange stars of any mass rotating at the equatorial mass-shedding limit, a gap always separates the ISCO and the stellar surface;

d) depending on the baryon mass of the star, the lowest ISCO frequency is attained either in the static configuration or in the configuration at the equatorial mass-shedding limit (see the figures);

e) the range of ISCO frequencies for Keplerian models is fairly narrow, and the dependence of ISCO frequency on the rotational frequency is well approximated by a linear function $f_{\text{ISCO}} \approx 0.8\, f$;

f) the least upper bound on the orbital frequency of stars modeled with the Dey et al. (1998) equation of state is obtained for a non-rotating star (the one whose radius is equal to the ISCO radius).

4. IMPLICATIONS FOR QPO MODELS

If some of the kHz QPO sources are Dey strange stars, then the QPO frequency has to be significantly below the maximum orbital frequency. In fact, in the discussion of QPOs in black hole candidates, the QPO frequency is taken to be the trapped mode frequency (Nowak, Wagoner 1990, Nowak et al. 1997), and it is seems worthwile to explore further the possibility that the highest frequency QPOs may appear at suborbital frequencies also in other systems, such as neutron star binaries and in AGNs.

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Figure 1. Frequency of the innermost marginally stable orbit as a function of stellar spin rate for one of the Dey models (in this model the maximum gravitational mass of a non-rotating, i.e., static star is $1.32M_\odot$). The sequences shown with thin continuous lines are labelled with their fixed baryon mass, in solar masses (the number in parentheses is the gravitational mass of the static configuration). The angular momentum increases along each curve, up to the Keplerian configuration, indicated with the thick dashed line. The thin dashed line connects the maxima of the curves.
Figure 2. Same as Fig. 1, for the other Dey model (here, the maximum gravitational mass of a static star is $1.44 M_\odot$). The mass-shed limit for this model is indicated with the thick solid line (and the corresponding limit for the model of Fig. 1 is shown again, for comparison, as a thick long-dashed line). The maxima of the curves are connected with the short-dashed line, and the corresponding thin long-dashed line from Fig. 1 is also reproduced for comparison.