RADIATIONAL OSCILLATIONS OF HYBRID STARS

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ABSTRACT

We study the effect of a quark and nuclear matter mixed phase on the radial oscillation modes of neutron stars. For this study, we have considered recent models from two classes of equations of state, namely, the relativistic mean field theoretical models and models based on realistic nucleon-nucleon interactions incorporating relativistic corrections and three-body nuclear interactions. We find that the effect of mixed phase is to decrease the maximum mass of a stable neutron star and to cause a kink in the radial oscillation frequencies at the onset of the mixed phase.

Subject headings: dense matter — elementary particles — stars: neutron

1. INTRODUCTION

Recently, there have been important developments in the determination of neutron star masses in binary systems. Whereas the best determination of neutron star masses in the range of 1.35 ± 0.04 M⊙ (Thorsett & Chakraborty 1999) is found for binary radio pulsars, limits on the masses of neutron stars from measurements of kilohertz quasi-periodic oscillation frequencies in low-mass X-ray binaries lie in the region of 2 M⊙ (Miller & Lamb 1998a; Miller, Lamb, & Cook 1998b; Miller, Lamb, & Psaltis 1998c, 1998d; see also van der Klis 2000). In addition, several X-ray binary masses have also been found to be high, viz, Vela X-1 and Cygnus X-2, with masses 1.8 ± 0.2 and 1.8 ± 0.4 M⊙, respectively (van Kerkwijk, van Paradijs, & Zuiderwijk 1998; Orosz & Kuulkers 1999). These large masses put severe constraints on the equation of state (EOS) of dense matter, and only very stiff EOSs are capable of sustaining such high masses. There are essentially two classes of EOSs for dense matter, one class based on relativistic mean field types of models with coupling constants treated as parameters to be fitted to observable quantities and the other based on realistic interactions between constituents obtained by fitting scattering data and using techniques of many-body theory to evaluate energy and pressure. Both classes of models, however, suffer from lack of sufficient experimental data. This situation is likely to be ameliorated by our understanding of the physics of heavy-ion collisions in laboratory experiments in the near future. In the core of neutron stars, where densities rise to a few times the normal nuclear densities, the state of matter is essentially unknown, and the possibility of a phase transition to constituent quark matter or to hadronic matter containing hyperons and/or meson condensates has been extensively studied in the literature (see, for example, Heiselberg & Pandharipande 2000, and references therein). All these phase transitions, whether first or second order, result in a softening of the EOS and thus aggravating the maximum mass limit. In a phase transition to quark matter, the neutron star may have a core of pure quark matter with a mantle of nuclear matter surrounding it, with the two phases coexisting in a first-order phase transition. Alternatively, one may have a so-called hybrid star, discussed by Glendenning (1992, 1997), wherein the quark and nuclear matter coexist in mixed phase with continuous pressure and density variation—a situation obtained by applying Gibb’s criteria to a two-component system.

One important aspect of various compact stars is the study of their radial modes of oscillation. Radial oscillations give information about the stability of the stellar structure under consideration and are thus quite important in distinguishing between various models of the stellar structure. In addition, as is well known, radial oscillations do not couple to gravitational waves; as a result, the equations governing radial oscillations are quite simple, and it is relatively easy to solve the eigenvalue problem that leads to the discrete set of eigenfrequencies for the system. The eigenfrequencies form a complete set, and hence it is possible to describe any arbitrary periodic radial disturbance as a superposition of its various eigenmodes.

For neutron stars, beginning with Chandrasekhar (1964), radial modes have been investigated in the literature for more than 30 years and for various nuclear matter EOSs (see, for example, Chanmugam 1977; Glass & Lindblom 1983; Vath & Chanmugam 1992; Kokkotas & Ruoff 2001). In view of the fact that only a few EOSs, viz, those of Wiringa, Fiks, & Fabrocini (1988) using A14+UV11 and U14+UV11 interactions and the recent EOS of Akmal, Pandharipande, & Ravenhall (1998) incorporating relativistic corrections and three-nucleon interactions in a new nucleon-nucleon interaction model (the Argonne A18 potential), are practically the only viable neutron star models capable of giving neutron star masses greater than 1.9 M⊙, we have picked them for the present study. In addition, we also consider the EOS given by Glendenning from the class of relativistic mean field theoretical models (Glendenning 1997). These equations invariably allow a phase transition in the core. In this paper, we study the effect of a mixed quark–nuclear matter core on radial oscillations of hybrid stars.

2. RADIATIONAL OSCILLATIONS OF A NONROTATING STAR

The equations governing the radial oscillations of a non-rotating star, using a static, spherically symmetric metric

$$ds^2 = -e^\nu dt^2 + e^\lambda dr^2 + r^2(d\theta^2 + \sin^2 \theta d\phi^2),$$

(1)
were given by Chandrasekhar (1964). The structure of the star in hydrostatic equilibrium is determined by the Tolman-Oppenheimer-Volkoff equations,

\[ \frac{dp}{dr} = -\frac{G(p + \rho)(m + 4\pi r^3 p)}{r^2(1 - 2GM/r)} , \]

(2)

\[ \frac{dm}{dr} = 4\pi r^2 \rho , \]

(3)

\[ \frac{d\nu}{dr} = \frac{2GM(1 + 4\pi r^3 p/m)}{r(1 - 2GM/r)} , \]

(4)

where we have put \( c = 1 \). Assuming a radial displacement \( \delta r \) with harmonic time dependence \( \delta r \sim \exp(i\omega t) \) and defining variables \( \xi = \delta r/r \) and \( \zeta = r^2 e^{-\nu} \xi \), the equation governing radial adiabatic oscillations is given by

\[ F \frac{d^2\zeta}{dr^2} + G \frac{d\zeta}{dr} + H \zeta = \omega^2 \zeta , \]

(5)

where

\[ F = -\frac{e^{2\nu-2\lambda}(\gamma p)}{p + \rho} , \]

\[ G = -\frac{e^{2\nu-2\lambda}}{p + \rho} \left[ \gamma p(\lambda + 3\nu) + \frac{d(\gamma p)}{dr} - 2\frac{\gamma p}{dr} \right] , \]

\[ H = \frac{e^{2\nu-2\lambda} \left[ \frac{4}{r} \frac{dp}{dr} + 8\pi Ge^{2\lambda} p(\rho + \rho) - \frac{1}{p + \rho} \left( \frac{dp}{dr} \right)^2 \right]}{p + \rho} , \]

(6)

\[ \lambda \text{ is related to the metric function through} \]

\[ e^{2\lambda} = \left[ 1 - \frac{2GM(r)}{r} \right] , \]

(7)

and \( \gamma \) is the adiabatic index, related to the speed of sound through

\[ \gamma = \frac{p + \rho dp}{p \frac{dp}{d\rho}} . \]

(8)

Equation (5) is solved under the boundary conditions

\[ \zeta(r = 0) = 0 , \quad \delta p(r = R) = 0 , \]

(9)

where \( \delta p(r) \) is given by

\[ \delta p(r) = -\frac{dp e^{\nu} \zeta}{dr^2} - \frac{\gamma p e^{\nu} d\zeta}{r^2 dr} . \]

(10)

Equation (5) with the boundary conditions in equation (11) represents a Sturm-Liouville eigenvalue problem for \( \omega^2 \) with the well-known result that the frequency spectrum is discrete. For \( \omega^2 > 0 \), \( \omega \) is real, and the solution is purely oscillatory, whereas for \( \omega^2 < 0 \), \( \omega \) is imaginary, resulting in exponentially growing unstable radial oscillations. Another important consequence is that if the fundamental radial mode \( \omega_0 \) is stable, so are the rest of the radial modes. For neutron stars, \( \omega_0 \) becomes imaginary at central densities \( \rho_c > \rho_c^{out} \), for which the star attains its maximum mass. For \( \rho_c = \rho_c^{out} \), the fundamental frequency \( \omega_0 \) vanishes and becomes unstable for higher densities, and the star is no longer stable. There also exists another unstable point at the lower end of the central density, namely, there exists a minimum mass for a stable neutron star and the frequency of the fundamental mode at the minimum mass again goes to zero.

3. RESULTS AND DISCUSSION

The only information required to obtain the structure of the star and eigenvalues of radial oscillation modes is knowledge of the EOS. For a given EOS, equations (2)–(5) are solved numerically by standard techniques under the boundary conditions in equation (11). While numerically integrating the equations for each EOS, we make sure that the eigenfrequency of the fundamental mode goes to zero at the maximum mass of the star. We have also checked that the frequency also vanishes at the minimum stable mass. For the EOS, as discussed in §1, we use two relativistic mean field theoretical models taken from Glendenning (1997) and two potential models incorporating relativistic corrections and three-body interactions given by Akmal et al. (1998). Both classes of models permit a mixed quark–nucleon phase in the core and correspond to matter as below:

**RFT 1H.**—This is a pure confined hadronic phase for \( n_B < 0.26 \text{ fm}^{-3} \), a mixed confined phase at intermediate densities, and pure quark matter at \( n_B > 1.17 \text{ fm}^{-3} \). Nuclear properties correspond to \( K = 240 \text{ MeV} \) and \( m^*/m = 0.78 \), where \( K \) is the compression modulus and \( m^* \) is the effective nucleon mass at nuclear saturation density \( n_0 = 0.15 \text{ fm}^{-3} \).

**RFT 2H.**—This is a confined hadronic phase for \( n_B < 0.26 \text{ fm}^{-3} \), a deconfined phase for \( n_B > 1.0 \text{ fm}^{-3} \), and a mixed phase in between. The quantity \( K = 300 \text{ MeV} \) and \( m^*/m = 0.78 \).

The models RFT 1 and RFT 2 correspond to pure hadronic phase occurring in the core of neutron stars without the existence of any quark phase.

**PMT 1H.**—Incorporating the Argonne A18 potential along with three-body interaction (the A18+UIX* model of Akmal et al. 1998) corresponds to a pure confined hadronic phase for \( n_B < 0.49 \text{ fm}^{-3} \), a mixed phase at intermediate densities, and a pure quark phase for \( n_B > 1.21 \text{ fm}^{-3} \).

**PMT 2H.**—Incorporating a relativistic boost correction \( \delta v \) along with three-body interaction UIX* and the Argonne A18 potential model corresponds to a pure confined hadronic phase for \( n_B < 0.57 \text{ fm}^{-3} \) and a pure quark phase for \( n_B > 1.57 \text{ fm}^{-3} \).

The models PMT 1 and PMT 2 refer to the above two models with a pure confined hadronic phase.

The quark matter in the above EOS models is described by the Bag model (Farhi & Jaffe 1984) with \( m_s = m_d = 0 \), \( m_u = 150 \text{ MeV} \), Bag constant \( B^{1/4} = 180 \text{ MeV} \), and \( \alpha_s = 0 \).

To illustrate the effect of mixed phase on neutron star parameters, namely, the mass–radius relationship and the frequency of radial oscillations, we have taken one model from each of the above two categories considered. Since the mass fraction contained in the crust of the star is a small fraction of the total star mass (<2%), we have used the earlier results (Baym, Pethick, & Sutherland 1971; Lorenz, Ravenhall, & Pethick 1993; Pethick, Ravenhall, & Lorenz 1995) of the EOS for matter densities \( \leq 0.1 \text{ fm}^{-3} \). In Figure 1 we have plotted the \( M-R \) curves, and we find that the effect of the existence of a mixed quark–nucleon matter phase in the core of neutron stars is to reduce the maximum mass. The effect is more pronounced for the relativistic mean field
theory model than for the potential model. For the RFT models, the radius corresponding to the maximum mass decreases, while for the potential models, it increases instead. For smaller mass, the two curves RFT 2 and RFT 2H (PMT 2 and PMT 2H) come very close to each other; this is to be expected, since these points correspond to low central densities, at which the effect of a mixed phase becomes negligible. In Figure 2 we have plotted the frequency of the fundamental mode and the next mode as a function of central density for the pure neutron and hybrid stars in the two categories, and we find that the frequency exhibits oscillatory behavior in the case of a neutron star with a mixed quark–nuclear matter core. In Tables 1–8, we provide the numerical results for the star parameters and
| $\rho_c \times 10^{14}$ (g cm$^{-3}$) | $R$ (km) | $M$ ($M_\odot$) | $z$ | $\nu_0$ (kHz) | $\nu_1$ (kHz) |
|---------------------------------|----------|-----------------|----|---------------|---------------|
| 30.04                           | 10.63    | 1.546           | 0.33| 0.96          | 6.22*         |
| 25.35                           | 10.95    | 1.550           | 0.31| 0.45          | 6.32          |
| 15.22                           | 12.09    | 1.496           | 0.25| 1.52          | 6.26          |
| 10.65                           | 12.78    | 1.394           | 0.22| 1.89          | 6.16          |
| 8.79                            | 13.07    | 1.314           | 0.21| 2.09          | 6.14          |
| 7.00                            | 13.35    | 1.187           | 0.17| 2.38          | 6.05          |
| 5.93                            | 13.48    | 1.072           | 0.14| 2.65          | 6.16          |
| 4.70                            | 13.58    | 0.868           | 0.11| 2.81          | 5.67          |
| 3.61                            | 13.70    | 0.608           | 0.07| 2.89          | 4.01          |
| 3.07                            | 13.86    | 0.471           | 0.05| 3.04          | 3.18          |

Note.—The asterisk signifies a model above the stability limit.

| $\rho_c \times 10^{14}$ (g cm$^{-3}$) | $R$ (km) | $M$ ($M_\odot$) | $z$ | $\nu_0$ (kHz) | $\nu_1$ (kHz) |
|---------------------------------|----------|-----------------|----|---------------|---------------|
| 32.07                           | 10.31    | 1.430           | 0.30| 0.77          | 6.27*         |
| 27.40                           | 10.68    | 1.434           | 0.28| 0.21          | 6.13          |
| 20.88                           | 11.40    | 1.425           | 0.26| 0.85          | 5.57          |
| 17.39                           | 11.68    | 1.409           | 0.24| 1.42          | 5.83          |
| 13.27                           | 12.20    | 1.346           | 0.21| 1.72          | 6.16          |
| 10.92                           | 12.66    | 1.268           | 0.19| 1.72          | 6.14          |
| 8.60                            | 13.22    | 1.160           | 0.16| 1.64          | 5.72          |
| 6.48                            | 13.68    | 1.041           | 0.13| 1.79          | 5.09          |
| 5.26                            | 13.83    | 0.958           | 0.12| 2.26          | 5.00          |
| 4.10                            | 13.89    | 0.807           | 0.09| 2.64          | 5.07          |
| 3.62                            | 13.97    | 0.651           | 0.07| 2.60          | 4.14          |
| 3.07                            | 14.17    | 0.495           | 0.06| 2.51          | 3.15          |
| 2.55                            | 14.81    | 0.344           | 0.03| 2.05          | 2.40          |

Note.—The asterisk signifies a model above the stability limit.

| $\rho_c \times 10^{14}$ (g cm$^{-3}$) | $R$ (km) | $M$ ($M_\odot$) | $z$ | $\nu_0$ (kHz) | $\nu_1$ (kHz) |
|---------------------------------|----------|-----------------|----|---------------|---------------|
| 26.47                           | 10.56    | 2.36            | 0.72| 1.27          | 7.71*         |
| 24.33                           | 10.70    | 2.37            | 0.70| 0.60          | 7.86          |
| 20.45                           | 11.02    | 2.35            | 0.65| 1.53          | 8.14          |
| 17.05                           | 11.36    | 2.30            | 0.58| 2.31          | 8.38          |
| 14.08                           | 11.69    | 2.19            | 0.48| 2.92          | 8.53          |
| 11.47                           | 11.98    | 1.96            | 0.39| 3.40          | 8.51          |
| 16.34                           | 12.17    | 1.61            | 0.28| 3.70          | 8.21          |
| 9.17                            | 12.20    | 1.38            | 0.23| 3.73          | 7.91          |
| 8.11                            | 12.21    | 1.13            | 0.17| 3.67          | 7.39          |
| 7.10                            | 12.23    | 0.87            | 0.13| 3.50          | 6.52          |
| 5.21                            | 12.35    | 0.65            | 0.09| 3.29          | 5.26          |
| 4.31                            | 12.80    | 0.45            | 0.06| 2.82          | 3.48          |
| 3.42                            | 13.41    | 0.35            | 0.04| 2.41          | 2.65          |

Note.—The asterisk signifies a model above the stability limit.

| $\rho_c \times 10^{14}$ (g cm$^{-3}$) | $R$ (km) | $M$ ($M_\odot$) | $z$ | $\nu_0$ (kHz) | $\nu_1$ (kHz) |
|---------------------------------|----------|-----------------|----|---------------|---------------|
| 31.40                           | 11.33    | 1.96            | 0.43| 1.96          | 5.33*         |
| 20.59                           | 11.49    | 1.97            | 0.43| 0.46          | 6.67          |
| 13.31                           | 11.89    | 1.89            | 0.38| 2.51          | 7.61          |
| 11.29                           | 12.05    | 1.80            | 0.34| 3.05          | 7.70          |
| 9.07                            | 12.15    | 1.65            | 0.29| 3.54          | 7.95          |
| 8.95                            | 12.18    | 1.56            | 0.27| 3.71          | 8.17          |
| 7.41                            | 12.21    | 1.33            | 0.22| 3.73          | 7.81          |
| 7.30                            | 12.22    | 1.18            | 0.18| 3.49          | 7.10          |
| 6.33                            | 12.23    | 0.92            | 0.13| 3.54          | 6.73          |
| 5.95                            | 12.26    | 0.82            | 0.12| 3.46          | 6.31          |
| 5.39                            | 12.32    | 0.70            | 0.10| 3.36          | 5.61          |

Note.—The asterisk signifies a model above the stability limit.
phases appear at a lower density as compared to the PMT because in RFT models, the mixed and pure quark-matter pure as well as a mixed-phase core. This is not surprising, observed between the RFT and PMT models for both a and from

On the other hand, if no high-mass neutron stars are found, decrease the fundamental frequency from about 3 to 2 kHz. Such high-mass neutron stars are, however, only stable for the core of neutron stars in RFT models alone. The higher radial frequencies in the PMT models are also due to a stiffer EOS in comparison to the RFT models. For neutron stars of masses \( \sim 1.4 \, M_\odot \), there is a significant change in the radial frequency of the fundamental mode: typically from \( \sim 2.1 \) to 1.4 kHz due to the existence of a mixed phase in the RFT models. A substantial difference in the frequencies, for example, from \( \sim 2 \) to \( \sim 3.75 \) kHz for the fundamental mode and from \( \sim 6 \) to \( \sim 8 \) kHz for the first excited mode, is observed between the RFT and PMT models for both a pure as well as a mixed-phase core. This is not surprising, because in RFT models, the mixed and pure quark-matter phases appear at a lower density as compared to the PMT models, and for \( \sim 1.4 \, M_\odot \) stars, such densities are reached in the core of neutron stars in RFT models alone. The higher radial frequencies in the PMT models are also due to a stiffer EOS in comparison to the RFT models. For neutron stars of higher mass, \( \sim 1.8 \, M_\odot \), the effect of a mixed phase is to decrease the fundamental frequency by about 30\%. Such high-mass neutron stars are, however, only stable for the PMT models. Thus, if neutron star measurements around \( \sim 1.4 \, M_\odot \) are confirmed, it would mean that there cannot be any significant phase transition at densities below roughly 5 times the nuclear density, and that the mixed phase would reduce the fundamental frequency from about 3 to 2 kHz. On the other hand, if no high-mass neutron stars are found, it would mean that accretion does not produce stars heavier than \( \sim 1.4 \, M_\odot \) and that heavier neutron stars are not stable, implying a soft EOS or a significant phase transition at few times the nuclear density. This result appears independent of the choice of the EOS, and again there is a drop of about 30\% in the fundamental frequency due to the mixed phase. There is, however, a caveat. The above inferences only hold if the hadronic matter is modeled by EOSs that are able to sustain the maximum mass of a stable neutron star in excess of \( 1.4 \, M_\odot \). There exist some EOSs in the literature, for example, the Brueckner-Hartree-Fock (BHF) EOS, where the maximum mass of a stable neutron star is \( \leq 1.2 \, M_\odot \). In such a case, the maximum mass increases because of the presence of a mixed phase in the core.

In conclusion, we find that the effect of the mixed phase is to decrease the maximum mass of the stable neutron star and to cause a kink in radial oscillation frequencies at the onset of the mixed phase. This result appears to be robust and independent of the EOS.

Note added in manuscript.—After the submission of this paper, a paper by Sahu, Burgio, & Baldo (2002) appeared in the Astrophysical Journal wherein they calculated the radial-mode frequencies of neutron stars with mixed phase. Their result that radial frequencies show a kink in the presence of a mixed phase and that a significant difference arises in radial frequencies between neutron stars with and without mixed phase are in conformity with our results. However, they find an increase in the maximum stable mass of neutron stars due to the presence of a mixed phase in the framework of the BHF EOS. This is in contrast to our result, in which we always find a decrease in the maximum mass due to a mixed phase. This, we believe, is due to the extremely soft EOS obtained in the BHF framework. The key point here is the relative stiffness/softness of the hadronic core vis-à-vis the mixed quark-matter core. A pure hadronic core stiffer than the mixed quark-matter core (and this is true for most EOSs) will always result in a decrease in maximum mass whenever a mixed phase exists in the core. Since the BHF EOS is a relatively softer EOS compared to the mixed-phase EOS, and this is the one used by Sahu et al., there is an increase in the maximum mass due to the mixed phase in their case. We thank the referee for drawing our attention to this paper.

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### TABLE 7

| \( \rho_0 \times 10^{14} \) (g cm\(^{-3}\)) | \( R \) (km) | \( M \) (\( M_\odot \)) | \( z \) | \( \nu_0 \) (kHz) | \( \nu_1 \) (kHz) |
|-----------------|--------|--------|--------|--------|--------|
| 27.10           | 10.03 | 2.188  | 0.68   | 0.64   | 8.49   |
| 17.49           | 10.82 | 2.066  | 0.52   | 2.90   | 9.88   |
| 13.47           | 11.22 | 1.831  | 0.39   | 3.55   | 8.64   |
| 12.28           | 11.34 | 1.711  | 0.35   | 3.71   | 8.81   |
| 11.14           | 11.43 | 1.569  | 0.30   | 3.82   | 8.64   |
| 10.05           | 11.51 | 1.403  | 0.25   | 3.88   | 8.38   |
| 9.01            | 11.57 | 1.220  | 0.21   | 3.88   | 8.01   |
| 8.01            | 11.63 | 1.025  | 0.16   | 3.79   | 7.51   |
| 5.19            | 12.17 | 0.520  | 0.07   | 3.11   | 4.40   |
| 3.42            | 14.20 | 0.269  | 0.03   | 1.80   | 2.22   |

### TABLE 8

| \( \rho_0 \times 10^{14} \) (g cm\(^{-3}\)) | \( R \) (km) | \( M \) (\( M_\odot \)) | \( z \) | \( \nu_0 \) (kHz) | \( \nu_1 \) (kHz) |
|-----------------|--------|--------|--------|--------|--------|
| 28.56           | 10.56 | 1.908  | 0.47   | 1.31   | 6.76*  |
| 24.64           | 10.65 | 1.911  | 0.46   | 0.50   | 7.25   |
| 20.04           | 10.83 | 1.898  | 0.44   | 1.86   | 7.83   |
| 17.13           | 11.00 | 1.861  | 0.42   | 2.48   | 8.15   |
| 14.97           | 11.16 | 1.801  | 0.38   | 2.93   | 8.30   |
| 13.24           | 11.29 | 1.716  | 0.35   | 3.30   | 8.34   |
| 11.78           | 11.41 | 1.606  | 0.31   | 3.62   | 8.37   |
| 11.12           | 11.45 | 1.542  | 0.29   | 3.76   | 8.43   |
| 10.49           | 11.49 | 1.471  | 0.27   | 3.86   | 8.48   |
| 9.42            | 11.55 | 1.295  | 0.22   | 3.89   | 8.18   |
| 8.40            | 11.62 | 1.104  | 0.18   | 3.84   | 7.74   |
| 7.42            | 11.70 | 0.908  | 0.14   | 3.70   | 7.10   |
| 6.48            | 11.84 | 0.721  | 0.10   | 3.48   | 6.14   |
| 5.56            | 12.04 | 0.589  | 0.08   | 3.25   | 5.05   |
| 4.65            | 12.57 | 0.426  | 0.05   | 2.84   | 3.48   |
| 3.77            | 13.68 | 0.305  | 0.04   | 2.14   | 2.45   |

Note.—The asterisk signifies a model above the stability limit.
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