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Stable ultracompact objects and an upper bound on neutron star masses

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Abstract. We have proposed a core-envelope model with stiffest equation of state [speed of sound equal to that of light] in the core and a polytropic equation with constant adiabatic index Γ_1 = [$\mathrm{d}lnP/\mathrm{d}ln\rho$] in the envelope and obtained a stable configuration with a maximum value of $u \cong 0.3574$ when the ratio of pressure to density at the core-envelope boundary reaches about 0.014. The maximum mass of neutron star based upon this model comes out to be $7.944M_\odot$, if the (average) density of the configuration is constrained by fastest rotating pulsar, with rotation period, $P_{rot} \cong 1.558$ ms, known to date. The average density of the configuration turns out to be 1.072×10^{14} g cm^{-3}. The model gives dynamically stable configurations with compaction parameter $u[\equiv (M/R)$, where $M \equiv$ mass and $R \equiv$ radius of the structure] $> (1/3)$ which are important to study Ultra-Compact Objects [UCOs]. The theoretically obtained maximum value of u is also important regarding millisecond oscillations seen during X-Ray burst (if they are produced due to spin modulation) from a rotating neutron star, because the maximum modulation amplitude depends only upon the compaction parameter and the observed value of this amplitude provides a tool for testing theoretical models of neutron stars. The M(envelope)/M(star) ratio corresponds to a value $\sim 10^{-2}$ which may be relevant in explaining the rotational irregularities in pulsars known as the timing noise and glitches.

Key words: dense matter – equation of state – stars: neutron

1. Introduction

Ultra Compact Objects (UCOs) with radius $R \leq 3M$ ($M \equiv$ mass of the star) are interesting entities. In principle, trapping of mass-less particles in UCOs potential well is possible or the object can oscillate in its quasinormal modes (Kembhavi & Vishveshwara 1980; Chandrasekhar & Ferrari 1991). Van Paradijs (1979) had pointed out the peculiar behavior of redshift for $R < 3M$. Existence of UCO was speculated by Iyer & Vishveshwara (1985), Iyer et al. (1985), and Lattimer et al. (1990). The first calculations, showing the existence of trapped photon or neutrino orbits inside such a UCO were made by Kuchowicz (1965) and de Felice (1969). Recently, Negi & Durgapal (1996) have obtained various types of trajectories of such particles (photons or neutrinos), for different initial conditions, inside a UCO characterized by parabolic density variation.

Furthermore, the rotation period and mass of dense matter objects with $R < 3M$ are important regarding sub-millisecond pulsars (smps). Haensel & Zdunik (1989) discussed the uniform rotation for a static mass of $1.442M_\odot$, and found that nearly all the existing realistic equations of state (EOSs) fail to provide a suitable model for smps. They found that in order to have a successful model for smps, the equation of state (EOS) should correspond to the matter of maximum stiffness [which corresponds to the condition that the speed of sound, $v = \sqrt{(dP/dE)}$ = speed of light $\equiv c$(= 1 in geometrized units) where P and E are, respectively, the pressure and the energy-density], that is,

$$P = [E - E_s] \tag{1}$$

and E_s is the value of E at the surface of the configuration.

Characteristics of the super-dense objects like neutron stars are based on the calculations of the EOS for the matter at very high densities. However, the nuclear interactions beyond the density of $\cong 10^{14}$ g cm^{-3} are empirically not well known (Dolan 1992) and all the known EOS are only extrapolations of the empirical results far beyond this density range. In this regard, various EOS based on theoretical manipulations are available in the literature (Arnett & Bowers 1977).

In order to obtain an upper limit for the neutron star masses various theoretical models have been proposed. As the status of EOS of nuclear matter cannot be established empirically, one can apply physical constraints to obtain an upper bound of neutron star mass. Brecher & Caporaso (1976) assumed that the speed of sound in the nuclear matter equals the speed of light and obtained a value of $4.8M_\odot$ as an upper limit of the neutron star masses by using EOS given by Eq. (1) and a surface density, $E_s = 2\times10^{14}$ g cm^{-3}. However, the matter described by this equation has a super-dense self-bound state at $P = 0$, which represent the 'abnormal state of matter' (Lee 1975; Haensel & Zdunik 1989). This 'abnormality' may be specified as the pressure vanishes at the order of nuclear densities, or in other words, the matter represent a super-dense self-bound state of matter even at vanishing small pressure, and the speed of sound remains equal to that of light in these conditions. This

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'abnormality' can be removed if we ensure continuity of all the metric parameters and their derivatives at the boundary of the structure.

Earlier, Rhoades & Ruffini (1974), without going into the details of the nuclear interactions, assumed that beyond a certain density $= 4.6 \times 10^{14}\,\mathrm{g\,cm^{-3}}$ [the range of densities where no extrapolated EOS is known], the EOS in the core is given by the criterion that the speed of sound attains the speed of light, that is, $(dP/dE) = 1$, and matched the core to an envelope with the BPS (Baym et al. 1971) EOS and obtained an upper limit for the neutron star mass as $3.2 M_\odot$.

Hartle (1978) emphasized that the maximum masses of neutron stars obtained in this manner involve a scale factor, say, $\kappa = [E_m/10^{14}\,\mathrm{g\,cm^{-3}}]^{-1/2}$, such that, the matching density, E_m, plays a sensitive role to obtain an upper bound on neutron star masses. Usually, κ is taken to be equal to or greater than one in all the conventional models. For the densities less than E_m, the matter composing the object is assumed to be known and unique. That is, the EOS of the envelope of these stars are chosen so that the 'abnormalities' in the sense mentioned above are removed. Friedman & Ipser (1987) calculated the masses of the neutron stars for different values of the matching densities by using EOS's in the envelope given by BPS and NV (Negele & Vautherin 1973), respectively, and concluded that for each case the mass in the envelope is negligible compared to that in the core containing the most stiff material. Furthermore, in all these cases the EOS chosen for the envelope are also uncertain and have little empirical support.

Another possibility which leads to an entirely different property of compact objects is that, in the absence of gravity high density baryonic matter is bound by purely strong forces. It can be shown that non-gravitationally bound bulk hadronic matter is consistent with nuclear physics data (Bahcall et al. 1989) suggesting that bulk hadronic matter is just as likely to be the correct description of matter at high densities as the conventional unbound hadronic matter. In general, the high-density non-gravitationally bound states of baryons are called "baryon matter" (Bahcall et al. 1990) and the terms "hadronic matter" or "quark Matter" are used for baryon matter described by theories of hadrons or quarks. Baryon matter refers to the saturating, large fermion number limit of these states in theories of either quarks or hadrons. Bahcall et al. (1990) gave an EOS, based upon effective field theory, which is consistent with all nuclear physics data, and low energy interaction data (Lynn et al. 1990), and they argued that possibly all the neutron stars are Q-stars with mass much larger than those obtained by conventional models. The term 'Q-star' is used for the objects whose self gravity is important, and also to distinguish these models from conventional models in which large numbers of baryons are not bound without gravity. In the Q-star model, baryon matter is a perfect fluid, and so the Oppenheimer-Volkoff equations can be integrated using the equation of state derived from a particular effective field theory. The Q-star boundary conditions define a stellar surface where the total hadronic pressure vanishes. At this point the energy density has not yet vanished, since the zero-hadronic-pressure state is just baryonic matter, but it drops exponentially to zero on a scale of fermis. Because there are no experimental data available for an EOS of many baryon system $[N >> 10^3]$ with densities close to nuclear density, E_m may take a value less than $\sim 10^{14}\,\mathrm{g\,cm^{-3}}$, and the upper limit on the maximum mass of compact objects which are not black holes (and also not neutron stars) could be arbitrarily large. Even if one is willing to dismiss the particular object resulting from the new EOS as being currently undiscovered in nature, the possibility that some EOS other than those previously extrapolated to nuclear densities may contain the correct physics at these densities indicated that the densities at which we know the form of EOS to be unique is lower than $10^{14}\,\mathrm{g\,cm^{-3}}$. In any case, the important point is that the density for which an EOS is known to be unique is lower than $10^{14}\,\mathrm{g\,cm^{-3}}$. Revealing the fact that the density range, $10^{10}\,\mathrm{g\,cm^{-3}} < E \leq 10^{15}\,\mathrm{g\,cm^{-3}}$, remains valid for Q-star equation of state, Bahcall et al. (1990) have obtained the stable Q-star masses as large as $400 M_\odot$ [for the matching density, $E_m = 10^{10}\,\mathrm{g\,cm^{-3}}$]. But, Lynn (priv. comm.) showed that to represent a physically viable model of Q-star, the upper mass limit would be significantly less than $400 M_\odot$.

Thus, we can summarize the whole scenario of EOS for the super-dense objects as follows:

(a) If we consider a hadronic matter we expect the density of the matter to vanish with the vanishing pressure, that is, near the surface of the star we must have an equation of state pertaining to a vanishing density. The model of the super-dense object may have a high density core represented by some stiff EOS surrounded by matter represented by EOS derived from the known nuclear interactions and extrapolated to densities at which these EOS are matched with the stiff EOS in the core. The matter represented by EOS corresponding to hadronic matter is surrounded by empirically known EOS [one or more in sequence] such that we obtain a vanishing small density at the surface of the star where the pressure vanishes.

The examples for such models are due to Rhoades & Ruffini (1974), Hartle (1978), and Friedman & Ipser (1987). Recently, Kalogera & Baym (1996) considered a model in which the most stiff core is matched to the WFF (Wiringa et al. 1988) EOS in the envelope, which is then matched to a crust with the EOS given by BPS. Glendenning (1992) considered a rotating structure with a core of most stiff EOS up to a density of $4.6 \times 10^{14}\,\mathrm{g\,cm^{-3}}$ surrounded by a constant pressure region which is then surrounded by BPS matter. Koranda et al. (1997) also considered a rotating structure with a core of most stiff EOS surrounded either by (i) an envelope of zero pressure or by (ii) a region of constant pressure which is covered by FPS (Lorenz et al. 1993) EOS.

(b) We may choose a baryonic matter surrounding the stiff core or an entire structure consisting of baryonic matter. In this case we are free to choose a finite density at the surface of the structure where the pressure vanishes. The baryonic matter represents a perfect fluid and can have densities lower than $10^{14}\,\mathrm{g\,cm^{-3}}$. One can get a large mass [but not arbitrary large (Lynn priv. comm.)] for the superdense objects [Q-stars] by introducing a lower value of E_m in the equation containing the scale factor κ.

Thus, to obtain a physically viable, upper mass limit for superdense objects, one may introduce certain constraint on the matching density, E_m, from the observational evidences known at present. The important observational evidences are:

(A) The minimum rotation period of the fastest rotating pulsars, PSR 1937 + 214, or PSR 1957 + 20 known to date is 1.558 ms [see, e.g., Müther et al. 1991, and references therein].

Assuming this pulsar as a Q-star, Hochron et al. (1993) used the observational fact (A) to obtain a constrained value of E_m [instead of assuming E_m], and then obtained a strict upper bound on Q-star masses as $5.3M_\odot$. However, based upon the observational data, Dolan (1992) had already shown that the mass of an unseen X-Ray binary (Cyg XR-1), $M = 6.3M_\odot$, may not necessarily represent a black-hole.

To avoid the discrepancy in the theoretical results of Hochron et al. (1993), and the observational data put forward by Dolan (1992), one may use values of E_m less than 10^{14} g cm^{-3}, and obtain a maximum mass larger than $6.3M_\odot$ for self-bound (Q) stars [by using a physically viable and causally consistent self-bound EOS (Negi & Durgapal 1999)]. Alternatively, it is also justified to construct a model of gravitationally bound star (neutron star) by choosing a core of the most stiff material [i.e., $(dP/dE) = 1$], matched to the envelope given by any physically viable and causally consistent EOS [not necessarily those given by BPS, NV, or FPS].

2. Removal of abnormality in the stiffest equation and upper bound on neutron star masses

We have tried to remove the abnormality in the stiffest EOS by the following method:

We truncate the density from a finite nuclear density to zero in a small region by assuming an envelope of the EOS of adiabatic polytrope (Tooper 1965), $\Gamma_1 = [\mathrm{d}lnP/\mathrm{d}ln\rho]$, where ρ is the rest mass density and Γ_1 is the (constant) adiabatic index. The use of a polytropic equation is justified because - (i) it gives a theoretical simplification which does not affect the results very much, and (ii) this choice also maintains the continuity of P, E, ν, λ and (dP/dE) at the core-envelope boundary.

The degree of softness of the envelope is determined by the boundary conditions to obtain the maximum value of u, and hence a maximum value of neutron star mass, because for a given value of rotation period, the maximum mass of the configuration depends only upon the corresponding maximum value of u [This is evident from Eq. (12), given later on].

3. Methodology and the core envelope model

For spherically symmetric and static configurations we make use of the metric

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

where ν and λ are functions of r alone. The Oppenheimer-Volkoff (O-V) equations, resulting from Einstein's field equations, for systems with isotropic pressure P and energy-density E can be written as

$$P' = -(P+E)[4\pi P r^3 + m]/r(r-2m) \qquad (3)$$

$$\nu'/2 = -P'/(P+E) \qquad (4)$$

$$m'(r) = 4\pi E r^2\,; \qquad (5)$$

where $m(r)$ is the mass, contained within the radius r, and the prime denotes radial derivative.

The core-envelope model consists of a core with most stiff EOS in the region $0 \leq r \leq b$ and an envelope with a polytropic EOS in the region $b \leq r \leq R$ as given below

(i) The core: $0 \leq r \leq b$

For the models of neutron stars considered here, we have chosen the core of most stiff material (Eq. (1)) as

$$P = (E - E_s)$$

where E_s is the value of density at the surface of the configuration, where pressure vanishes.

(ii) The envelope: $b \leq r \leq R$

The envelope of this model is given by the equation of state

$$P = K\rho^{\Gamma_1} \qquad (6)$$

or

$$(E - \rho) = P/(\Gamma_1 - 1).$$

where K is a constant to be worked out by the matching of various variables at the core-envelope boundary.

At the boundary, $r = b$, the continuity of $P(= P_b), E(= E_b)$, and $r(= r_b)$ require

$$K = P_b/(E_b - [P_b/(\Gamma_1 - 1)])^{\Gamma_1} \qquad (7)$$

where Γ_1 is given by (see, e.g., Tooper 1965)

$$\Gamma_1 = [(P+E)/P](dP/dE).$$

Thus, the continuity of (dP/dE), at the boundary gives

$$\Gamma_1 = 1 + (E_b/P_b). \qquad (8)$$

Thus, the continuity of P, E, ν, λ, and (dP/dE) at the core-envelope boundary is ensured, for the static and spherically symmetric configuration.

The coupled Eqs. (3), (4), (5), are solved along with Eqs. (1) and (6) for the boundary conditions (7) and (8) [at the core-envelope boundary, $r = b$], and the boundary conditions, $P = 0$, $m(r = R) = M$, $e^\nu = e^{-\lambda} = (1 - 2M/R) = (1 - 2u)$ at the external boundary, $r = R$.

For the sake of numerical simplification, we assign the central density, $E_0 = 1$. It is seen that the degree of softness of the envelope is restricted by the inequality, $(P_b/E_b) \geq 0.014$. For the minimum value of $(P_b/E_b) \cong 0.014$, we obtain various quantities, such as, core mass, M_b, core radius, r_b, density at the core-envelope boundary, E_b, total mass, M, and the corresponding radius, R, of the configuration in dimensionless form as shown in Table 1 for various assigned values of the central pressure to density ratio, (P_0/E_0).

Table 1. Properties of the causal core-envelope models, with a core given by the most stiff EOS, $(dP/dE) = 1$, and the envelope is characterized by the polytropic EOS, $(\mathrm{d}lnP/\mathrm{d}ln\rho) = \Gamma_1$, such that, all the parameters, P, E, ν, λ, and the speed of sound, $(dP/dE)^{1/2}$, are continuous at the core-envelope boundary, r_b. The maximum value of $u[\equiv (M/R) \cong 0.3574]$ for the structure is obtained (Fig. 1), when the minimum value of the ratio of pressure to density at the core-envelope boundary, (P_b/E_b), reaches about 0.014. The maximum value of the binding-energy per baryon, $\alpha_r[\equiv (M_r - M)/M_r$, where M_r is the rest mass of the configuration$] \cong 0.2441$, also occurs for the maximum stable value of u. The subscript '0' and 'b' represent, the values of respective quantities at the centre, and at the core-envelope boundary. z_R stands for the surface redshift. The calculations are performed for an assigned value of the central energy-density, $E_0 = 1$. The slanted values represent the limiting case upto which the structure remains dynamically stable. Dimensionless values of various quantities for $P_b/E_b \cong 0.014$

(P_0/E_0)	r_b	E_b	M_b	R	M	u	α_r	z_R	z_0
0.1110	0.1886	0.9017	0.0260	0.2012	0.0313	0.1558	0.1001	0.2052	0.3473
0.1562	0.2181	0.8559	0.0391	0.2282	0.0444	0.1946	0.1290	0.2795	0.4977
0.2012	0.2410	0.8101	0.0511	0.2489	0.0558	0.2243	0.1512	0.3467	0.6515
0.2564	0.2639	0.7542	0.0643	0.2712	0.0692	0.2550	0.1751	0.4287	0.8573
0.3100	0.2832	0.6998	0.0759	0.2887	0.0798	0.2763	0.1917	0.4949	1.0598
0.4000	0.3127	0.6086	0.0934	0.3176	0.0971	0.3058	0.2152	0.0648	1.4513
0.5070	0.3477	0.5001	0.1130	0.3522	0.1164	0.3304	0.2334	0.7168	2.0020
0.5661	0.3690	0.4401	0.1239	0.3733	0.1271	0.3405	0.2395	0.7703	2.3633
0.6010	0.3829	0.4047	0.1306	0.3870	0.1337	0.3455	0.2419	0.7988	2.6033
0.6410	0.4003	0.3642	0.1388	0.4043	0.1417	0.3504	0.2434	0.8282	2.9084
0.7040	*0.4329*	*0.3002*	*0.1531*	*0.4376*	*0.1564*	*0.3574*	*0.2441*	*0.8724*	*3.4925*
0.7070	0.4347	0.2971	0.1539	0.4395	0.1572	0.3577	0.2441	0.8744	3.5242
0.7151	0.4396	0.2890	0.1559	0.4443	0.1592	0.3583	0.2436	0.8783	3.6085
0.7238	0.4450	0.2801	0.1582	0.4497	0.1614	0.3590	0.2430	0.8833	3.7055

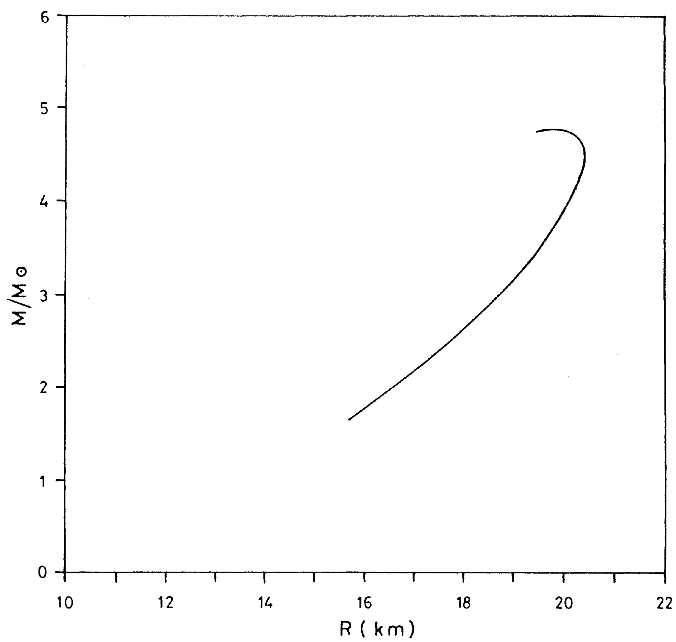

Fig. 1. Mass-Radius diagram of the model for an assigned value of $E = 2 \times 10^{14}$ g cm^{-3} at the core-envelope boundary r_b, such that the ratio of pressure to density (P_b/E_b) at r_b reaches about 0.014. The pressure, energy-density, ν, λ, and the speed of sound, $(dP/dE)^{1/2}$ are continuous at the core-envelope boundary.

To determine the stability of the models given in Table 1, we need to draw the mass-radius diagram for the structures. For this purpose, we have normalized the boundary density, $E = 2 \times 10^{14}$ g cm^{-3}, and obtained the mass-radius diagram as shown in Fig. 1 [Notice that the value of E_b chosen in this way (and hence also the mass and the radius obtained in conventional units as shown in Fig. 1) is purely arbitrary. These values have nothing to do with the actual maximum mass and the corresponding radius of the stable neutron star obtained in the present paper. The choice of E_b does not affect the maximum value of u upto which the structure remains dynamically stable]. The maximum stable value of u of the whole configuration is obtained as 0.3574, which would determine the maximum mass of the stable neutron star from the knowledge of the rotation period of PSR 1937 + 214, or PSR 1957 + 20. It is interesting to note that for this value of u, the binding energy per baryon, $\alpha_r[\equiv (M_r - M)/M_r$, where M_r is the rest-mass (Zeldovich & Novikov 1978) of the configuration] also approaches maximum ($\cong 0.2441$) as shown in Table 1.

Koranda et al.(1997) have obtained the following empirical formula for the class of minimum period EOSs which is fairly insensitive to the matching density

$$P_{rot,min}(\mathrm{ms}) = 0.740[M_{max}/M_\odot]^{-1/2}[R_{max}/10\mathrm{km}], \quad (9)$$

where $P_{rot,min}$ is the (minimum) rotation period of the maximal (uniformly) rotating configuration, and M and R are maximum mass and the corresponding size of the non-rotating configuration. Rewriting Eq. (9) in terms of compaction parameter, $u[\equiv M/R]$, and angular velocity $\Omega_{max}(\equiv 2\pi/P_{rot,min})$ we obtain

$$\Omega_{max} = 2.21 \times 10^{10}[u_{max}^{1/2}/R_{max}\ (\mathrm{cm})\ ]\ \mathrm{s}^{-1} \quad (10)$$

where u_{max} is the maximum value of u of the non-rotating configuration, such that the configuration becomes dynamically unstable when u exceeds u_{max}, and R represents the corresponding radius of the configuration.

Let us denote the average density of the configuration by E_{av} [because $M = (4/3)\pi E_{av} R^3$, or $3u = 4\pi E_{av} R^2$] by using Eq. (10) we obtain

$$E_{av}(\,\mathrm{g\,cm^{-3}}) = 6.59 \times 10^6 [\Omega_{max}(\,\mathrm{s^{-1}})]^2, \tag{11}$$

and,

$$M_{max}\ (\mathrm{cm}) = [3u_{max}^3 / 4\pi E_{av}(\mathrm{cm}^{-2})]^{1/2}. \tag{12}$$

Thus, the average density of the configuration depends only upon the rotation period, and not upon the compaction parameter u. Therefore, it is clear from Eqs. (11) - (12) that for a given value of the rotation period, P_{rot}, the maximum mass of the stable configuration depends only upon the maximum value of u. For $P_{rot} = 1.558$ ms, Eq. (11) gives the average density, E_{av}, of the configuration as 1.072×10^{14} g cm^{-3}, the substitution of $u_{max} \cong 0.3574$ in Eq. (12) gives the maximum mass of the configuration, $M_{max} = 7.944 M_\odot$ and the corresponding radius, $R_{max} = 32.761$ km.

The ratio, M(envelope)/M(star), is about $\sim 10^{-2}$, which may be relevant to explain rotational irregularities in pulsars known as timing noise and glitches (see, e.g., D' Allessandro 1997, and references therein).

4. Results and conclusions

We have proposed a model with stiffest equation of state [speed of sound equal to that of light] in the core and a polytropic equation with constant adiabatic index $\Gamma_1 = [\mathrm{d}lnP/\mathrm{d}ln\rho]$ in the envelope. We obtain a stable configuration with a maximum value of $u \cong 0.3574$, when the minimum ratio of pressure to density at the core-envelope boundary reaches about 0.014. In our model all the metric parameters including their first derivatives and the speed of sound are continuous at the core-envelope boundary and at the exterior boundary of the structure. The maximum u for this core-envelope model comes out to be nearly as large as that obtained by using the most stiff EOS [which is abnormal in the sense that the nuclear matter does not correspond to the state of self-bound matter] throughout the structure. The structures are dynamically stable and gravitationally bound even for the value of compaction parameter, $u \geq (1/3)$, thus giving a suitable model for studying the Ultra-compact Objects [UCOs].

The maximum mass of neutron star based upon this model comes out to be $7.944 M_\odot$, if the (average) density ($\cong 1.072 \times 10^{14}$ g cm^{-3}) of the configuration is constrained by the fastest rotating pulsar (rotation period, $P_{rot} \cong 1.558$ ms), known to date.

The M(envelope)/M(star) ratio corresponds to a value $\sim 10^{-2}$ which may be relevant in explaining the rotational irregularities in pulsars known as the timing noise and glitches.

The maximum value of u is also important regarding millisecond oscillations seen during X-Ray burst (if they are produced due to spin modulation) from a rotating neutron star (if the rotation is not enough rapid to modify the exterior Schwarzschild geometry), because the maximum modulation amplitude depends only upon the compaction parameter [see, e.g., Strohmayer et al. 1998; Miller & Lamb 1998; and references therein] and the observed value of this amplitude provides a powerful tool for testing theoretical models of neutron stars.

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