Exotic phases and limiting maximum mass of rotating neutron stars

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Introduction

Neutron stars are the most dense form of observable matter known to us. They posses extremely high core densities and gravitational fields. Neutron stars are created as rapidly rotating remnant cores of massive stars which end up their lives in super-novae explosions.

The observed properties of massive neutron stars are the key tools for testing the theories of high density interaction and the predictions of general relativity. In this work, we calculate the theoretical upper limit for the mass and deformation of rapidly rotating neutron stars by validating the equation of state (EoS) in low frequency regime using the properties of the recently observed most massive pulsar PSR J0348+0432. This pulsar rotates with frequency $f_{obs} = 25.5606361937675(4)$ Hz and has a mass of $2.01 \pm 0.04\ M_\odot$, where $M_\odot$ is the solar mass [1].

The configurations of rotating neutron stars are numerically computed by solving the Einstein field equations for stationary axisymmetric spacetime using the `LORENE` library [5].

Formalism for EoS

A. Polytropic EoS model

We simulate high density phase transitions with exotic phases through piecewise polytropic EoSs which are given by [4]

$$p(n) = K_0 n^{\Gamma_0},\ \epsilon(n) = \mu_0 n + \frac{p(n)}{\Gamma_0 - 1},\ n \leq n_t \quad (1)$$

$$p(n) = K_1 n^{\Gamma_1},\ \epsilon(n) = \mu_0 (1+a) n + \frac{p(n)}{\Gamma_1 - 1},\ n \geq n_t \quad (2)$$

where n is the baryon number density, p is pressure and ϵ is the energy density. K and Γ are polytropic coefficient and adiabatic index, respectively. μ_0 is the baryon rest mass, n_t is the phase transition density and the factor $(1 + a)$ signifies a change in chemical potential after the phase transition. The continuity of pressure at the transition density is satisfied by the four parameters, K_0, Γ_0, n_t & Γ_1 of the EoS. The lower limit of n_t is the nuclear saturation density $n_0 = 0.153$ fm^{-3}. The lower limit of Γ is estimated to be 4/3 by comparing the EoS with the polytrope of an ultra relativistic degenerate gas. K_0 is treated as a free parameter and adjusted to reproduce the limiting mass of the star in the range $(1.97 - 2.05)M_\odot$ at frequency f_{obs}.

B. Realistic EoS model

We extend the calculations of Ref. [2] to describe neutron star matter with hyperons and antikaons considering the recently observed two solar mass neutron star. The Lagrangian reads

$$\begin{aligned}\mathcal{L} = \textstyle\sum_B \bar{\psi}_B \big[g_{\sigma B}\sigma - m_B - \gamma^\mu (g_{\rho B}\tau_{3B}.R_\mu \\ + g_{\omega B} V_\mu)\big] \psi_B + \tfrac{1}{2}\left(1 + \eta_1 \tfrac{g_{\sigma N}\sigma}{m_n} + \tfrac{\eta_2}{2}\tfrac{g_{\sigma N}^2\sigma^2}{m_n^2}\right) \\ m_\omega^2 V_\mu V^\mu + \tfrac{\zeta_0 g_{\omega N}^2 (V_\mu V^\mu)^2}{4!} + \left(1 + \eta_\rho \tfrac{g_{\sigma N}\sigma}{m_n}\right) \\ m_\rho^2 \mathrm{tr}(R_\mu R^\mu) - m_\sigma^2\sigma^2 \left(\tfrac{1}{2} + \tfrac{\kappa_3 g_{\sigma N}\sigma}{3! m_n} + \tfrac{\kappa_4 g_{\sigma N}^2\sigma^2}{4! m_n^2}\right) \\ + \left[D_\mu^* K^* D^\mu K - m_k^{*2} K^* K\right], \quad (3)\end{aligned}$$

where the symbols carry their usual meanings. The last term represents antikaon-nucleon interaction [3] including higher order couplings which appear only in extended relativistic mean field models. The EoS is obtained from the diagonal elements of the energy-momentum tensor.

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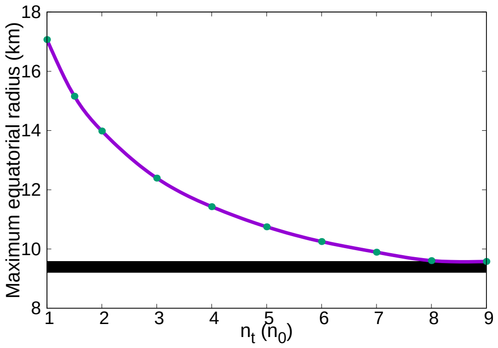

FIG. 1: Calculated radius with two phase EoS at frequency f_{obs}. n_0 is the nuclear saturation density (0.153 fm^{-3}). The black strip represents the allowed radius with one phase EoS ($\Gamma_0 = 3$).

Results and discussions

Neutron stars are well described by relativistic polytropes with $4/3 \leq \Gamma \leq 3$ [4]. We start with a highly stiff single phase EoS in the low density region with $\Gamma_0 = 3$, which constrains the radius in a narrow range of $(9.21 - 9.58)$ km. We then use EoS with exotic phase, where $\Gamma_0 = 3$ and $4/3 \leq \Gamma_1 \leq 3$ and calculate the allowed radius as a function of phase transition density. Other parameters of EoS are adjusted to reproduce the limiting mass $(1.97-2.05)$ $M_\odot$ at frequency f_{obs}. It can be seen from Fig. 1 that maximum allowed radius is extremely sensitive to phase transitions at lower densities. Minimum allowed radius is however same in all cases with the value 9.21 km (when $\Gamma_1 = 3$).

TABLE I: Properties of two solar mass neutron star with realistic EoS model. R_{eq} is the equatorial radius, β is the compactness parameter ($GM/R_{eq}c^2$) and f_k is the Keplerian frequency.

EoS	$R_{eq}(km)$	β ($f = f_{obs}$)	$f_k(Hz)$
G1	12.00	0.251427372322	1212.93
NL1	13.92	0.217303616495	1103.65
NL3	13.98	0.217074483344	1068.56

We calculate the properties of the star with realistic EoSs including hyperons and antikaons. The hyperon-nucleon and antikaon-nucleon interactions (x_σ and U_K) [2] adjusted to reproduce the limiting mass near 2.05 $M_\odot$ at frequency f_{obs} (Table I).

TABLE II: Properties of rapidly spinning neutron stars using the validated realistic EoSs. Last row in each block represents data calculated at Keplerian frequency.

EoS	$f(Hz)$	$M_{lim}(M_\odot)$	$R_{eq}(km)$	R_p/R_{eq}
G1	f_{obs}	2.046	12.002	0.999
	400	2.066	12.039	0.973
	800	2.141	12.608	0.889
	1212.93	2.390	17.656	0.538
NL1	f_{obs}	2.052	13.924	0.999
	400	2.094	14.207	0.956
	800	2.273	15.313	0.807
	1103.65	2.623	19.401	0.528
NL3	f_{obs}	2.058	13.984	0.999
	400	2.105	14.271	0.953
	800	2.296	15.406	0.804
	1168.56	2.569	19.814	0.518

The properties of rapidly rotating neutron stars calculated with validated EoSs are shown in Table II. This indicates that the theoretical upper limit on mass of the rotating neutron star lies near 2.6 $M_\odot$. In other words, if the most massive neutron star starts accreting, its rotation frequency and mass will increase at the same time. While the increased gravity due to the added mass tries to collapse the star, the centrifugal force due to the increased angular frequency restricts it. In such cases, we predict that a rotating neutron star can acquire upto 2.6 $M_\odot$ before gravitational collapse.

References

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