

Part 9
Population and Neutron Star
Properties

Section D. Interior of Neutron Stars

A microscopic study of neutron stars' structure

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Abstract. Starting from the nuclear interactions which are used to calculate the properties of atomic nuclei, we derive a new equation of state (EOS) for neutron star matter. With this realistic EOS, we calculate the structure of non-rotating neutron stars.

The *core* of a neutron star (NS) consists of a quantum liquid composed of an uncharged mixture of neutrons, protons, electrons and muons in equilibrium with respect to the weak interaction (β -stable nuclear matter)¹.

In the present contribution, we report recent calculations by Baldo, Bombaci & Burgio (1997) of an equation of state (EOS) for β -stable nuclear matter, using the Brueckner–Bethe–Goldstone many-body theory (see *e.g.* Baldo 1999). The basic input of this microscopic approach is the bare nucleon-nucleon (NN) interaction, which reproduces the experimental features of NN scattering experiments and the deuteron properties. We use the Argonne V14 (or the Paris) two-body nuclear force, implemented by the Urbana VII model for the three-body force (UVII). We refer to the corresponding equations of state as EOS1 (Argonne V14 + UVII), and EOS2 (Paris + UVII). For comparison, we also employ one of the EOS by Wiringa, Ficks & Fabrocini (1988), calculated using the variational method with correlation operators. We consider the case relative to the Argonne V14 + UVII nuclear interactions (hereafter WFF EOS).

With these realistic EOSs we solve the equations for stellar structure in general relativity to calculate various properties of non-rotating NS. The properties for the maximum mass configuration are listed in Tab. 1.

The value of the proton fraction $x \equiv Z/A$ is an important ingredient to model the thermal evolution of a neutron star. In fact, if the proton fraction in the core of the star, is above a critical value x^{Urca} , the so called direct Urca processes, can occur (Lattimer et al. 1991). If they occur, neutrino emission and neutron star cooling rate are enhanced by a large factor compared to the standard cooling scenario. The threshold properties for the onset of direct Urca processes and the central proton fraction for $M = M_{max}$ and $M = 1.4M_{\odot}$ are

¹At ultra-high density, matter might undergo a transition to other exotic hadronic components (see *e.g.* Prakash et al. 1997) like hyperons, a K^- condensate or a deconfined phase of quark matter). Here, we do not consider such a possibility.

Table 1. Properties of the maximum mass configuration obtained from different equations of state. M_G is the gravitational (maximum) mass, R is the corresponding radius, ρ_c the central density, n_c the central number density ($n_0 = 0.16 \text{ fm}^{-3}$), P_c the central pressure, M_B the baryonic mass. Masses are expressed in unit of the mass of the sun M_\odot .

EOS	M_G/M_\odot	R(km)	$\rho_c(\text{g/cm}^3)$	n_c/n_0	$P_c(\text{dyne/cm}^2)$	M_B/M_\odot
EOS1	1.790	9.66	$3.08 \cdot 10^{15}$	8.53	$1.02 \cdot 10^{36}$	2.084
EOS2	1.917	9.49	$3.19 \cdot 10^{15}$	8.45	$1.44 \cdot 10^{36}$	2.262
WFF	2.130	9.40	$3.00 \cdot 10^{15}$	7.81	$2.01 \cdot 10^{36}$	2.632

Table 2. Threshold properties for the onset of direct Urca processes. x^{Urca} , $n^{Urca}(\text{fm}^{-3})$, and $M^{Urca} \equiv M_G(n^{Urca})$ are respectively the threshold proton fraction, number density and gravitational mass (the entry "no" means that direct Urca processes do not occur). $x_c(M_{max})$ is the central proton fraction for the maximum mass configuration and $x_c(1.4 M_\odot)$ for the star with $1.4 M_\odot$ gravitational mass.

EOS	x^{Urca}	n^{Urca}	M^{Urca}	$x_c(M_{max})$	$x_c(1.4 M_\odot)$
EOS1	0.139	0.65	1.40	0.230	0.139
EOS2	0.139	0.54	1.24	0.265	0.165
WFF	no	no	no	0.045	0.066

reported in Tab. 2. Within our model, neutron stars with a central density higher than n^{Urca} develop inner cores in which direct Urca processes are allowed. Therefore, NS with masses above M^{Urca} can undergo very rapid cooling, depending on the strength of superfluidity in the interior of the NS.

The equilibrium sequences of rapidly rotating NS in general relativity, and the Keplerian frequency at the innermost stable circular orbit, for the same equations of state, have been calculated by Datta, Tampan & Bombaci (1998).

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