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Uniformly rotating neutron stars in the global and local charge neutrality cases

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Abstract

In our previous treatment of neutron stars, we have developed the model fulfilling global and not local charge neutrality. In order to implement such a model, we have shown the essential role by the Thomas–Fermi equations, duly generalized to the case of electromagnetic field equations in a general relativistic framework, forming a coupled system of equations that we have denominated Einstein–Maxwell–Thomas–Fermi (EMTF) equations. From the microphysical point of view, the weak interactions are accounted for by requesting the β stability of the system, and the strong interactions by using the σ–ω–ρ nuclear model, where σ, ω and ρ are the mediator massive vector mesons. Here we examine the equilibrium configurations of slowly rotating neutron stars by using the Hartle formalism in the case of the EMTF equations indicated above. We integrate these equations of equilibrium for different central densities ρ_c and circular angular velocities Ω and compute the mass M, polar R_p and equatorial R_{eq} radii, angular momentum J, eccentricity ϵ, moment of inertia I, as well as quadrupole moment Q of the configurations. Both the Keplerian mass-shedding limit and the axisymmetric secular instability are used to construct the new mass–radius relation. We compute the maximum and minimum masses and rotation frequencies of neutron stars. We compare and contrast all the results for the global and local charge neutrality cases.

Keywords: Nuclear physics; Astrophysics; Neutron stars; Quantum hadrodynamics; Field theory

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1. Introduction

We have recently shown [22,23,2] that the equations of Tolman–Oppenheimer–Volkoff (TOV) [30,21] traditionally used to describe the neutron star equilibrium configurations, are superseded once the strong, weak, electromagnetic and gravitational interactions are taken into account. Instead, the Einstein–Maxwell system of equations coupled with the general relativistic Thomas–Fermi equations of equilibrium have to be used; what we called the Einstein–Maxwell–Thomas–Fermi (EMTF) system of equations. While in the TOV approach the condition of local charge neutrality, $n_e(r) = n_p(r)$ is imposed (see e.g. Haensel et al. [12] and references therein), the EMTF approach requests the less stringent condition of global charge neutrality, namely

$$\int \rho_{\rm ch}\, d^3r = \int e\big[n_p(r) - n_e(r)\big]\, d^3r = 0, \tag{1}$$

where $\rho_{\rm ch}$ is the charge density, e is the fundamental electric charge, n_i is the particle density of the i-species, and the integral is carried out on the entire volume of the system.

The Lagrangian density taking into account all the interactions include the free-fields terms $\mathcal{L}_g$, $\mathcal{L}_\gamma$, $\mathcal{L}_\sigma$, $\mathcal{L}_\omega$, $\mathcal{L}_\rho$ (respectively for the gravitational, the electromagnetic, and the three mesonic fields), the three fermion species (electrons, protons and neutrons) term $\mathcal{L}_f$ and the interacting part in the minimal coupling assumption, $\mathcal{L}_{\rm int}$ [23,2]:

$$\mathcal{L} = \mathcal{L}_g + \mathcal{L}_f + \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_\gamma + \mathcal{L}_{\rm int}, \tag{2}$$

where[1]

$$\mathcal{L}_g = -\frac{R}{16\pi}, \qquad \mathcal{L}_f = \sum_{i=e,N} \bar{\psi}_i\big(i\gamma^\mu D_\mu - m_i\big)\psi_i,$$

$$\mathcal{L}_\sigma = \frac{\nabla_\mu\sigma\nabla^\mu\sigma}{2} - U(\sigma), \qquad \mathcal{L}_\omega = -\frac{\Omega_{\mu\nu}\Omega^{\mu\nu}}{4} + \frac{m_\omega^2\omega_\mu\omega^\mu}{2},$$

$$\mathcal{L}_\rho = -\frac{\mathcal{R}_{\mu\nu}\mathcal{R}^{\mu\nu}}{4} + \frac{m_\rho^2\rho_\mu\rho^\mu}{2}, \qquad \mathcal{L}_\gamma = -\frac{F_{\mu\nu}F^{\mu\nu}}{16\pi},$$

$$\mathcal{L}_{\rm int} = -g_\sigma\sigma\bar{\psi}_N\psi_N - g_\omega\omega_\mu J_\omega^\mu - g_\rho\rho_\mu J_\rho^\mu + eA_\mu J_{\gamma,e}^\mu - eA_\mu J_{\gamma,N}^\mu,$$

where the description of the strong interactions between the nucleons is made through the σ–ω–ρ nuclear model in the version of Boguta and Bodmer [6]. Thus $\Omega_{\mu\nu} \equiv \partial_\mu\omega_\nu - \partial_\nu\omega_\mu$, $\mathcal{R}_{\mu\nu} \equiv \partial_\mu\rho_\nu - \partial_\nu\rho_\mu$, $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$ are the field strength tensors for the ω^μ, ρ and A^μ fields respectively, ∇_μ stands for covariant derivative and R is the Ricci scalar. We adopt the Lorenz gauge for the fields A_μ, ω_μ, and ρ_μ. The self-interaction scalar field potential is $U(\sigma)$, ψ_N is the nucleon isospin doublet, ψ_e is the electronic singlet, m_i states for the mass of each particle-specie and $D_\mu = \partial_\mu + \Gamma_\mu$, being Γ_μ the Dirac spin connections. The conserved currents are $J_\omega^\mu = \bar{\psi}_N\gamma^\mu\psi_N$, $J_\rho^\mu = \bar{\psi}_N\tau_3\gamma^\mu\psi_N$, $J_{\gamma,e}^\mu = \bar{\psi}_e\gamma^\mu\psi_e$, and $J_{\gamma,N}^\mu = \bar{\psi}_N(1/2)(1+\tau_3)\gamma^\mu\psi_N$, being τ_3 the particle isospin.

The nuclear model is fixed once the values of the coupling constants and the masses of the three mesons are fixed: for instance in the NL3 parameter set Lalazissis et al. [20] used in [2] and in this work we have $m_\sigma = 508.194$ MeV, $m_\omega = 782.501$ MeV, $m_\rho = 763.000$ MeV,

[1] We use spacetime metric signature $(+,-,-,-)$ and geometric units $G = c = 1$ unless otherwise specified.