Studying the Uncertainty of Parameters of Asymmetric Dense Nuclear Matter Based on Massive Pulsar Observations Data

Balázs Endre Szigeti, Gergely Gábor Barnaföldi, Péter Pósfay, Antal Jakovác
szigeti.balazs@wigner.hu, barnafoldi.gergely@wigner.hu,
posfay.peter@wigner.hu,jakovac.antal@wigner.hu

ELTE EÖTVÖS LORÁND UNIVERSITY

WIGNER

Abstract

We analyzed recent astronomical observation data of pulsar masses and radii of PSR J0740+6620, PSR J0348+0432, and PSR J1614-2230 measurements, based on the extended, self-interacting version of the Walecka model. In our study, we used mean-field approximation to determine the EoS used to describe the neutron star at the core and solved the TOV equations to determine the M-R diagrams. We assumed that the observed pulsars are maximal-mass compact stars, thus we could apply the core approximation. Based on the linear relation between the microscopic and macroscopic parameters of neutron stars evaluated by our model, we estimated the average Landau mass and compressibility values, which were found to be in agreement with nuclear data.

Results

Assuming maximal mass stars, we found linear dependence of both observables, the mass and radius of the maximal mass star, M_{maxM} and R_{maxM} on the m_L, where we used the saturated nuclear matter for the compressibility and asymmetry energy. The functions were fitted independently with 0.8% and 17% theoretical uncertainty, respectively, following:

$$M_{maxM}[\mathrm{M}_\odot] = 5.418 - 0.0043\, m_L[\mathrm{MeV}] \ ,$$
$$R_{maxM}[\mathrm{km}] = 19.04 - 0.0104\, m_L[\mathrm{MeV}] \ .$$

After we fixed the Landau mass by the MMS observation we can also obtain a one-parameter linear equation between the compressibility, K and the mass and radius of the MMS compact star with $< 2\%$ and $< 14\%$ theoretical uncertainty,

$$M_{maxM}[\mathrm{M}_\odot] = 1.940 + 0.000880\, K\, [\mathrm{MeV}] \ ,$$
$$R_{maxM}[\mathrm{km}] = 9.248 + 0.00718\, K\, [\mathrm{MeV}] \ .$$

One can see that the K-equations have positive gradient which means that increasing compressibility makes an MMS compact star more larger and massive.

The Model

To describe the interior structure of the compact star we used is the σ-ω model, which can be naturally extended by further interactions [1, 2].

$$\mathcal{L} = \overline{\Psi}\left(i\partial\!\!\!/ - m_N + g_\sigma\sigma - g_\omega \omega\!\!\!/ + g_\rho \rho\!\!\!/^a \tau_a\right)\Psi + \overline{\Psi}_e\left(i\partial\!\!\!/ - m_e\right)\Psi_e - \lambda_3\sigma^3 + \lambda_4\sigma^4$$
$$+\frac{1}{2}\sigma\left(\partial^2 - m_\sigma^2\right)\sigma - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\,\omega^\mu\omega_\mu - \frac{1}{4}\rho^a_{\mu\nu}\,\rho^{\mu\nu\,a} + \frac{1}{2}m_\rho^2\,\rho^a_\mu\,\rho^{\mu\,a} \ ,$$

where $\Psi = (\Psi_n, \Psi_p)$ is the vector of proton and neutron fields, m_N, m_σ, m_ω, m_ρ are the masses of the nucleons and σ is the scalar-, and ω, ρ are (iso-)vector mesons respectively. Moreover g_σ, g_ω, and g_ρ are the Yukawa couplings corresponding to the nucleon-meson interactions. The kinetic terms corresponding to the ω and ρ meson can be written in the following forms,

$$\omega_{\mu\nu} = \partial_\mu\omega_\nu - \partial_\nu\omega_\mu \quad \text{and} \quad \rho^a_{\mu\nu} = \partial_\mu\rho^a_\nu - \partial_\nu\rho^a_\mu + g_\rho\epsilon^{abc}\rho^b_\mu\rho^c_\nu .$$

We are taking the mean-field approximation at zero temperature and finite chemical potential of this model. The fluctuations of the ω and ρ vector meson fields are relative heavy thus their contribution can be neglected in the loop-integrals. We obtain the free energy:

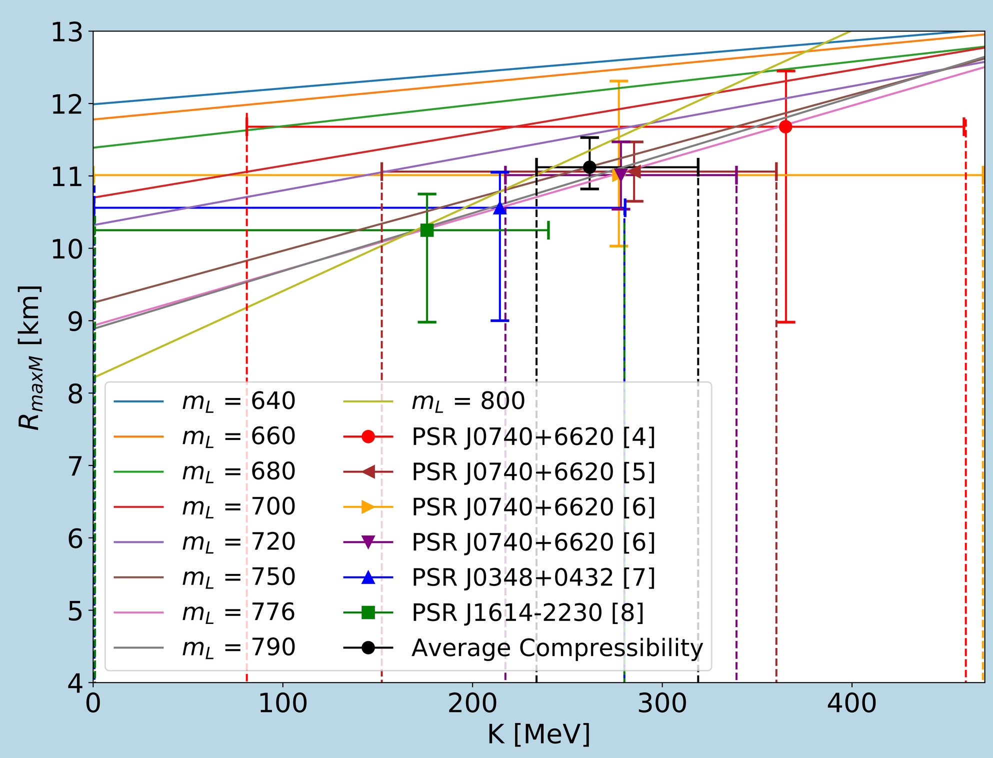
$$f_T = f_F(m_N - g_\sigma\sigma, \mu_p - g_\omega\omega + g_\rho\rho) + f_F(m_N - g_\sigma\sigma, \mu_n - g_\omega\omega - g_\rho\rho)$$
$$+ f_f(m_e, \mu_e) + \frac{1}{2}m_\sigma^2\sigma^2 + U_i(\sigma) - \frac{1}{2}m_\omega^2\omega^2 - \frac{1}{2}m_\rho^2\rho^2$$

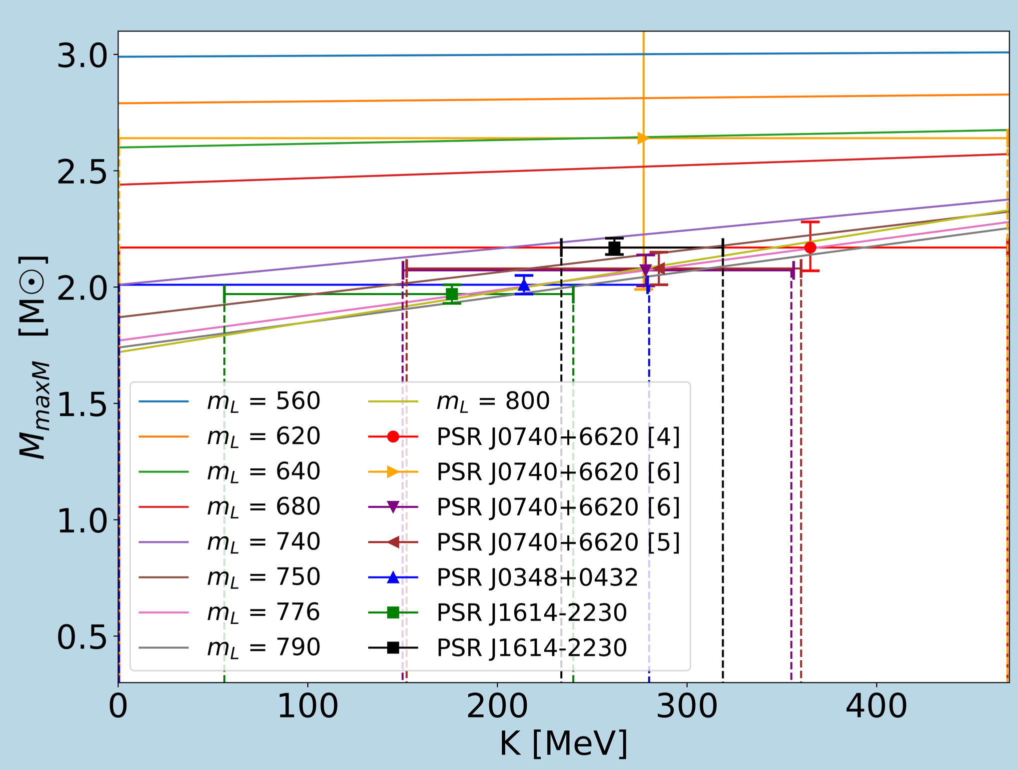
For the fit of the free parameters of this model the nuclear saturation data were used [3], except for the Landau mass and compressibility. These two parameters are kept free and determined by comparing the mass radius diagrams corresponding to different values of the Landau mass to neutron star observations. We also determined the average of Landau masses $m_L = 752.46^{+49.1}_{-42.5}$ MeV and mean compressibility $K = 261.7^{+57.2}_{-28.0}$ MeV, which agrees well with the saturated nuclear matter data and with our recent works [9, 2].

Ref.	Pulsar	$M_{maxM}[\mathrm{M}_\odot]$	m_L[MeV]	K[MeV]	R_{maxM}[km]
[4]	PSR J0740+6620	$2.17^{+0.11}_{-0.10}$ *	$748.39^{+63.3}_{-57.2}$	$351.8^{+115}_{-84.5}$	$11.25^{+1.06}_{-1.04}$
[7]	PSR J0348+0432	$2.01^{+0.04}_{-0.04}$ *	$785.25^{+20.0}_{-20.3}$	$206.4^{+42.7}_{-20.5}$	$10.87^{+0.82}_{-0.80}$
[8]	PSR J1614-2230	$1.97^{+0.04}_{-0.04}$ *	$794.47^{+20.1}_{-20.4}$	$170.0^{+15.5}_{-20.9}$	$10.77^{+0.82}_{-0.80}$
[6]	PSR J0740+6620	$2.07^{+0.07}_{-0.07}$ *	$778.14^{+15.3}_{-15.5}$	$278.2^{+60.9}_{-60.8}$	$11.01^{+0.46}_{-0.47}$
[6]	PSR J0740+6620	$2.64^{+1.98}_{-0.65}$	639.42^{+159}_{-125}	277.3^{+257}_{-178}	$12.39^{+1.30}_{-0.98}$ *
[5]	PSR J0740+6620	$2.08^{+0.07}_{-0.01}$ *	$769.12^{+16.9}_{-16.9}$	$285.1^{+54.8}_{-54.8}$	$11.06^{+0.41}_{-0.41}$

Measured pulsar masses and radii data denoted by '$*$', and assuming that these are maximal-mass neutron stars. We calculated the mass-radius diagram by the well-known Tolman – Oppenheimer – Volkoff equations (TOV). To focus our investigation on the effect of the nuclear matter we integrated the TOV equations with core approximation condition Ref. [1]. The mass and radius data calculated this generally can be considered a conservative approximation of the neutron star parameters, however in the case of the maximum mass star the deviations from the normal case are insignificant.

Maxmimal Mass Compact Stars





On the figure we plotted the projections of the $M_{maxM}(m_L, K)$ and $R_{maxM}(m_L, K)$ curves, where the K-dependent one-parameter linear equations are determined for various m_L values. Pulsar mass and radii data from Table 1. are also plotted with color markers, where the error bars include both theoretical uncertainties from the phenomenological approach and errors from the astrophysical observation. Our results agree well with our previous results [1, 2] and also with a Bayesian analysis carried out on this extended σ-ω model [9, 2].

References

[1] P. Pósfay, G. G. Barnaföldi and A. Jakovác,
[2] G. G. Barnaföldi *et al*, Eur. Phys. J. ST **229** no.22-23, 3605-3614 (2020)
[3] J. Meng, Relativistic Density Functional for Nuclear Structure, International Review of Nuclear Physics (World Scientific Publishing Company, 2016),
[4] H. Cromartie *et al*, Nat. Astron. **4**, 72-76 (2019)
[5] M.C. Miller *et al*, arXiv:2105.06979 [astro-ph.HE] (2021)
[6] T.E. Riley *et al*, arXiv:2105.06980 [astro-ph.HE] (2021)
[7] J. Antoniadis *et al*, Science **340**, 6131 (2013)
[8] Demorest, P.*et al*,Nature **467**, 1081-1083 (2010).
[9] D. Alvarez-Castillo *et al*, Eur. Phys. J. ST **229** no.22-23, 3615-3628 (2020)

Acknowledgements

Authors acknowledge for NKFIH (OTKA) grants No. K123815, K135515, PHAROS (CA16214) cost action, and for the computational resources by the Wigner Scientific Computing Laboratory (former Wigner GPU Laboratory).