Estimating Compressibility by Maximal-mass Compact Star Observations

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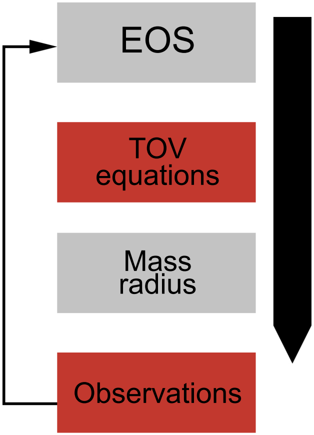
Motivation



- Different nuclear models produce very similar neutron star parameters?
  - What is the reason behind this?
  - How can it be circumvented?
  - What can be learned from neutron star measurements?
- What is the connection between the microscopic parameters of the nuclear matter and neutron star observables?

Extended Walecka-model ($\sigma - \omega$ model)

- **Scalar meson** $U_i(\sigma) = \gamma_3\sigma^3 + \gamma_4\sigma^4$
- Electron kinetic and mass
- Kinetic terms: $\Psi = (\Psi_p, \Psi_n)$

$$\mathcal{L} = \bar{\Psi}(i\partial\!\!\!/ - m_N + g_\sigma\sigma - g_\omega\omega\!\!\!/ + g_\rho\rho\!\!\!/^2\tau_a)\Psi + \bar{\Psi}_e(i\partial\!\!\!/ - m_e)\Psi_e + \frac{1}{2}\sigma(\partial^2 + m_\sigma^2)\sigma - U_i(\sigma)$$

$$- \frac{1}{4}\omega^{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu - \frac{1}{4}\rho^{a\mu\nu}\rho^a_{\mu\nu} + \frac{1}{2}m_\rho^2\rho^a_\mu\rho^a_\mu$$

- Vector mesons

$$\omega_{\mu\nu} = \partial_\mu\omega_\nu - \partial_\nu\omega_\mu \qquad \rho^a_{\mu\nu} = \partial_\mu\rho^a_\nu - \partial_\nu\rho^a_\mu + g_\rho\epsilon^{abc}\rho^b_\nu\rho^c_\nu \quad (1)$$

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Mean-Field Approximation

- Mean-field approximation at zero temperature and finite chemical potential
- Tree-level: $\omega = \omega_0$ and $\rho_0^3 = \rho$
- β-equilibrium: $\mu_n = \mu_p + \mu_e$
- Baryon number and electric charge conservation
- **Free-energy:**

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

- **Fermionic pressure:**

$$f_F(T, m, \mu) = -2T \int \frac{d^3k}{(2\pi)^3} \ln \left[1 + e^{-\beta(E_k - \bar{\mu})} \right] \quad (3)$$

Data Fit

The free parameters of the model are determined by using nuclear saturation data [Gle97].

The values used to fit the model

1. **Binding energy:** $B = -16.3$ **MeV**
2. Saturation density: $n_0 = 0.153 fm^{-3}$
3. Nucleon effective mass $m^* = 0.6 m_N$
4. Nucleon Landau mass $m_L = 0.83 m_N$
5. Compressibility: $K = 240$ MeV
6. Asymmetry energy $a_{sym} = 32.5$ MeV

$$m_L = \frac{k_F}{v_F} \qquad v_F = \left.\frac{\partial E_k}{\partial k}\right|_{k=k_F} \qquad m_L = \sqrt{k_f^2 + m_{N,eff}^2} \qquad (4)$$

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Mass-Radius Diagrams

- Static, spherically symmetric space-time
- Tolman-Oppenheimer-Volkoff equations (TOV)

$$\frac{\mathrm{d}p(r)}{\mathrm{d}r} = -\frac{G\epsilon(r)m(r)}{r^2}\left[1+\frac{p(r)}{\epsilon(r)}\right]\left[1+\frac{4\pi r^3 p(r)}{m(r)}\right]\left[1-\frac{2Gm(r)}{r}\right]^{-1}$$
$$\frac{\mathrm{d}m(r)}{\mathrm{d}r} = 4\pi r^2\epsilon(r) \tag{5}$$

- We used core-crust model for the calculation
- Low density region: well known BPS nuclear EoS
- The calculated R in this case corresponds to the radius of the neutron star core

Maximal Mass Stars

- Determine the mass and radius of the maximal mass stars (MMS)
- Most relevant parameter: the Landau mass m_L. ($\delta m_L \overset{10x}{>} \delta K$)
- Linear dependence M_{maxM}, R_{MaxM} on the m_L
- Landau mass was optimized with fixed K, a_{sym}.

$$M_{maxM}[\mathrm{M}_\odot] = 5.418 - 0.0043\, m_L[\mathrm{MeV}], \quad S = 0.008, \tag{6}$$

$$R_{maxM}[\mathrm{km}] = 19.04 - 0.0104\, m_L[\mathrm{MeV}], \quad S = 0.172. \tag{7}$$

After fixing the m_L by the MMS observations we can also obtain linear, one-parameter dependence on the parameter K.

$$M_{maxM}[\mathrm{M}_\odot] = 1.766 + 0.0011K\,[\mathrm{MeV}], \quad S = 0.014, \tag{8}$$

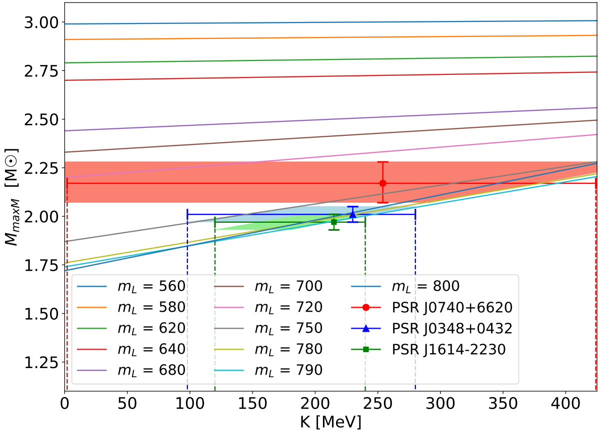
$$R_{maxM}[\mathrm{km}] = 8.880 + 0.0077K\,[\mathrm{MeV}], \quad S = 0.14. \tag{9}$$

Observation Data

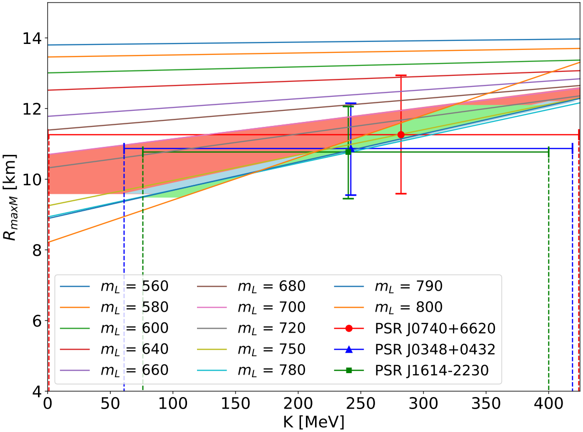
Type	Pulsar	M_{maxR}[$M_\odot$]	m_L[MeV]	K[MeV]	R_{maxR}[km]
MMS	PSR J0740+6620	$2.17^{+0.11}_{-0.10}$ *	$748.39^{+63.3}_{-57.2}$	$351.8^{+115}_{-84.5}$	$11.25^{+1.06}_{-1.04}$
MMS	PSR J0348+0432	$2.01^{+0.04}_{-0.04}$ *	$785.25^{+20.0}_{-20.3}$	$206.4^{+42.7}_{-20.5}$	$10.87^{+0.82}_{-0.80}$
MMS	PSR J1614-2230	$1.97^{+0.04}_{-0.04}$ *	$794.47^{+20.1}_{-20.4}$	$170.0^{+15.5}_{-20.9}$	$10.77^{+0.82}_{-0.80}$

Table 1: The Landau mass, m_L and compressiblity, K values calculated via eq. (6)- from measured pulsar mass data, assuming that these are maximal-mass neutron stars. Maximal radius of the maximal-mass neutron star is also calculated form eq. (7). [Ant+13; al20; Dem10]

K dependence of the mass of MMS



K dependence of the radius of MMS



Landau mass values:

Remark I.

The range of 550 MeV$< m_L <$ 800 MeV is compatible with effective nucleon mass given by the various equation of state at saturation [Klä+06].

Remark II.

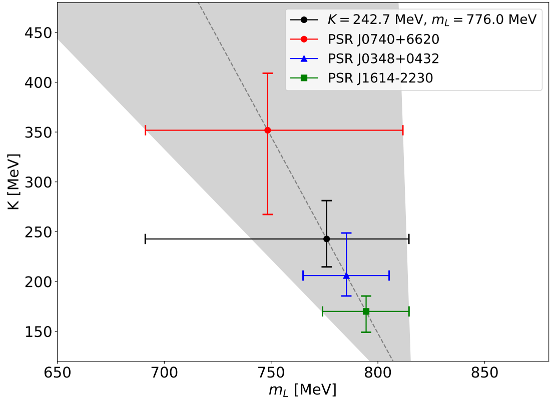
- Average Landau mass: $m_L = 776.0^{+38.5}_{-84.9}$ MeV
- Bayesian Analysis I. [Alv+20a]: (PSR J0030+0451 + PSR 0740+6620 + GW170817)
  - $m_L = 750^{+15}_{-15}$ MeV
- Bayesian Analysis II. [Alv+20b]: (PSR J0740+6620 + PSR J0348+0432 + GW170817 + PSR J0030+0451)
  - $m_L = 750^{+15}_{-15}$ MeV

Joint formula for mass and radius of MMS

Dependence on these variables are not independent any more, but can be factorized into joint formulae, including higher-order, cross-product terms for the $M_{maxM}(m_L, K)$ and $R_{maxM}(m_L, K)$ respectively:

$$M_{maxM} = 6.29 - 0.00574 m_L[\text{MeV}] - 0.00379 K[\text{MeV}] + 0.00000524 m_L \cdot K[\text{MeV}^2]$$
$$R_{maxM} = 27.51 - 0.0239 m_L[\text{MeV}] - 0.0241 K[\text{MeV}] + 0.0000411 m_L \cdot K[\text{MeV}^2]$$

Compressiblity and Landau mass map



The nuclear model parameter space of K and m_L is plotted with values estimated from pulsar data of PSR J0740+6620, PSR J0348+0432, and PSR J1614-2230. Fit line and average microscopic data value with uncertainty is also marked [Ant+13; al20; Dem10].

Summary

Input:

- Extended Walecka-model
- Mean-Field Approximation

Method:

- Tollman-Oppenheimer-Volkoff equation
- Using the linear relations between the microscopic and macroscopic parameters
- Observation data

Results:

- Landau mass: $m_L = 776.0^{+38.5}_{-84.9}$ MeV
- Compressibility: $K = 242.7^{57.2}_{-28.0}$ MeV
- Radius: $R = 10.96^{+1.35}_{-1.00}$ km

References

Thank you for your time. Questions?

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