The hyperonic volume of MSP J0740+6620

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Introduction

Neutron stars (NSs) are highly compact objects formed during the gravitational collapse of massive stars after supernovae explosions. The primary ingredients of NSs are neutrons and protons, but the detailed composition is not precisely known. Exotic phase transitions at high densities decrease the maximum allowed mass of NSs. It can be expected that the recently observed most massive pulsar MSP J0740+6620 [1] will rule out the existence of hyperons in NS cores. In this work, we explain the existence of hyperons in MSP J0740+6620 without violating any of the astronomical and nuclear physics constraints on the equation of state (EoS) of NS matter.

Formalism

The Covariant Density Functional Theory (CDFT) is utilized to estimate the EoS of NS matter. The effective mean-field Lagrangian density, after curtailing the contributions of photons and phi-mesons, is given by [2–4]

$$\begin{aligned}\mathcal{L} &= \sum_B \bar{\psi}_B[\gamma^\mu \left(i\partial_\mu - g_{\omega B}V_\mu - g_{\rho B}\ \vec{\tau}_B\cdot\vec{R}_\mu\right) \\ &- (m_B - g_{\sigma B}\sigma)]\psi_B + \sum_l \bar{\psi}_l\,(-m_l)\,\psi_l \\ &- \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2 V_\mu V^\mu + \frac{1}{2}m_\rho^2\vec{R}_\mu\cdot\vec{R}^\mu \\ &- \left(\frac{\kappa_3}{3!}\frac{g_{\sigma N}}{m_n}\sigma + \frac{\kappa_4}{4!}\frac{g_{\sigma N}^2}{m_n^2}\sigma^2\right)m_\sigma^2\sigma^2 \\ &+ \frac{1}{4!}\zeta_0 g_{\omega N}^2(V_\mu V^\mu)(V_\mu V^\mu) \\ &+ \Lambda_v g_{\omega N}^2 g_{\rho N}^2(V_\mu V^\mu)(\vec{R}_\mu\cdot\vec{R}^\mu), \qquad (1)\end{aligned}$$

where the symbols have their usual meanings. For simplicity, we assume that all hyperons interact similarly with the meson fields. The hyperon-meson coupling constants are therefore quantified by the ratios

$$x_\sigma = \frac{g_{\sigma H}}{g_{\sigma N}},\ x_\omega = \frac{g_{\omega H}}{g_{\omega N}},\ x_\rho = \frac{g_{\rho H}}{g_{\rho N}}, \qquad (2)$$

where H and N denote the hyperons and nucleons, respectively. The scalar coupling $x_\sigma \lesssim 0.8$ [4]. If we assume $x_\rho = x_\sigma$, x_ω can be calculated using

$$x_\omega = \frac{x_\sigma g_{\sigma N}\sigma(\rho_0) + U_\Lambda(\rho_0)}{g_{\omega N}V_0(\rho_0)}. \qquad (3)$$

Here, $U_\Lambda(\rho_0) = -28$ MeV is the potential depth of Λ hyperon in normal nuclear matter, and ρ_0 is the nuclear saturation density. The EoS is calculated from the diagonal elements of energy-momentum tensor, which is thereafter utilized for solving the relativistic structure equations for NSs. We have constrained the EoSs with recent determinations of the maximum allowed NS mass [1, 7, 8], and the radii limits of canonical NSs [5, 6].

Results and Discussions

Fig. 1 shows the non-rotating NS sequence calculated using the hyperonic NL3 and FSU2H EoSs. The NL3h EoS is generated at $x_\sigma = 0.76$, and the FSU2Hh EoS at $x_\sigma = 0.8$. The suffix 'h' denotes the inclusion of hyperons. The NS sequence of a valid EoS must end up in the shaded region, and intersect the yellow line also. The sequence of NL3h EoS ends up in the gray area but doesn't intersect the yellow line, thereby violating the imposed size constraints. The FSU2Hh EoS ends up in the gray region and also intersects the yellow line. The inclusion of ζ_0 and Λ_v terms in the Lagrangian have modified the EoS as per the astrophysical requirements. Existence of hyperons in NS cores

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is therefore not ruled out by available observations.

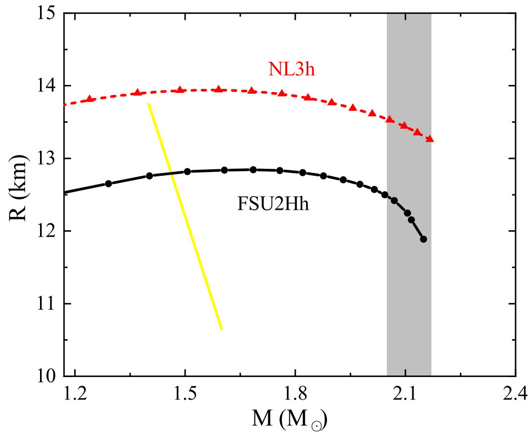

FIG. 1: Non-rotating NS sequences calculated with hyperonic EoSs. The gray shaded region depicts $2.05 \leq M \leq 2.17 M_\odot$, where $M_\odot$ is the solar mass. The yellow line is the pictorial representation of NS radii limits which constrain the EoSs.

We now investigate the hyperonic content in the recently observed most massive pulsar MSP J0740+6620 [1]. This NS has a mass of $2.14^{+0.10}_{-0.09}$ $M_\odot$, and a rotation frequency of ν = 346.5 Hz. Fig. 2 shows the density profiles of neutrons and the Σ^- hyperons in MSP J0740+6620 calculated with FSU2Hh EoS at its observed rotation frequency. The neutron profile extends up to the NS surface, and the Σ^- profile extends up to the edge of the hyperonic region. Along the equatorial axis, the NS radius is $\approx$ 12.1 km, with hyperons existing up to $\approx$ 9.7 km. Along the polar axis, the NS radius is $\approx$ 11.95 km, with hyperons up to $\approx$ 9.55 km. The hyperonic volume is $\approx$ 3750 km^3, and the total NS volume is $\approx$ 7350 km^3. These calculations therefore suggest that almost half the volume of MSP J0740+6620 is hyperonic.

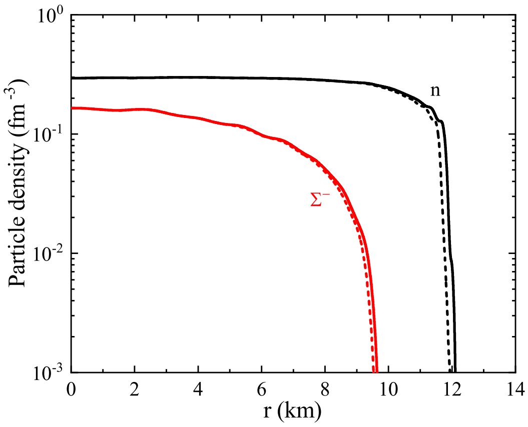

FIG. 2: Density profiles of neutrons and Σ^- hyperons in MSP J0740+6620 calculated with FSU2Hh EoS. M and ν denote the NS mass and rotation frequency, respectively. r is the distance from NS center. The solid and dotted lines represent the profiles along equatorial and polar axis, respectively.

References

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