Massive neutron stars with hadron-quark transition

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Generally every transition in dense neutron star (NS) matter to the phases with exotic components causes a strong softening of the equation of state (EOS) and the maximum mass (\( M_{\text{max}} \)) for corresponding NSs contradicts the recent observation of the \( 2M_{\odot} \)-NS (PSR J1614-2230), i.e. \( M_{\text{max}} < < 2M_{\odot} \).

Here we ask whether \( M_{\text{max}} \geq 2M_{\odot} \) is made possible for NSs with hadron(H)-quark(Q) transition by a new approach to the construction of the EOS, characterized as “three-window model”. We divide the EOS into three parts [1][2], i.e., H-EOS for \( \rho \leq \rho_H \), HQ-EOS for \( \rho_H \leq \rho \leq \rho_Q \) and Q-EOS for \( \rho \geq \rho_Q \), motivated by the consideration that pure hadronic EOS becomes uncertain with increasing \( \rho \) because of finite size hadrons composed of quarks and also pure quark matter EOS gets unreliable due to the deconfined-confined transition with decreasing \( \rho \). The basic idea is to supplement the very poorly known HQ-EOS by sandwiching it in between the relatively certain H-EOS and Q-EOS and obtain HQ-EOS by a phenomenological interpolation. We use a realistic H-EOS form a G-matrix-based effective interaction including hyperons and take the Q-EOS from NJL model with a vector interaction.

As an interpolation function, we take \( p(x) = ax^m + bx^n + c \) with \( p \) the pressure and \( x = \rho / \rho_0 \) (\( \rho_0 \) being the nuclear density). The energy density \( \varepsilon(x) \) is derived from \( p(x) = x^2 \frac{\partial}{\partial x} \left( \frac{\varepsilon(x)}{x} \right) / \varepsilon(x) \) and parameters inherent are determined by the matching conditions for \( p(x) \) and \( \varepsilon(x) \) at boundaries \( x_H \) and \( x_Q \). The solution is searched with respect to a set of \( \{ x_H, x_Q, m, n \} \) under the conditions \( \partial p / \partial x \geq 0 \) and \( v_s \) (sound velocity) \( \leq c \). It is found that \( M_{\text{max}} \sim (2-3)M_{\odot} \) is possible as far as \( x_H \sim 2, x_Q \sim (5-7) \) and Q-EOS is stiff. This suggests that the H-Q transition in NS cores has a potentiality resolving the \( 2M_{\odot} \)-problem and supports the results in [2] discussed from a percolation picture.