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A Systematic Analysis of Hybrid Stars Using a Hadronic Equation of State Suitable for Core-Collapse Supernovae

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Our long-term goal is to develop a new supernova equation of state that meets the observational 2 $M_\odot$ neutron star constraint and that includes quark matter. In this work, we perform a parameter scan to systematically investigate the hadron-quark phase transition in cold neutron stars using the state-of-the-art supernova equation of state HS(DD2) for the hadronic phase. We find neutron star configurations with maximum masses above 2 $M_\odot$ and even above the maximum mass of HS(DD2). Our results show good agreement with other parameter scans.

KEYWORDS: equation of state, hybrid star, neutron star, QCD

1. Introduction

The composition of matter at extreme densities, as e.g. observed in neutron stars or core-collapse supernovae (CCSN), is highly uncertain. At such densities, new degrees of freedom as e.g. quarks should be considered. However, the measurements of 2 $M_\odot$ neutron stars [1,2] set a crucial constraint on equations of state (EOSs), especially those that consider such new degrees of freedom. Our aim is to develop a new supernova EOS that considers quark matter and fulfills the 2 $M_\odot$ neutron star constraint. In this work, we analyze the cold hybrid star configurations using the method developed by Alford et al. in [3]. For the hadronic phase we take the state-of-the-art supernova EOS HS(DD2) [4] and compare our results with the ones of [3] where different hadronic EOSs were used.

2. Hybrid Star Model

To systematically analyze hybrid stars, we use the simple model introduced by Alford et al. in [3]. Only the hadronic EOS is varied to the HS(DD2) EOS. In the following, a brief overview of the hybrid star model is given.

2.1 Hadronic Matter

Hadronic matter is described by the HS(DD2) EOS [4, 5] , which is a supernova EOS available at finite temperature and variable proton fraction and density in form of a table. HS(DD2) is based on density-dependent relativistic mean-field theory and is in good agreement with experimental constraints. HS(DD2) has a high maximum mass of 2.42 $M_\odot$ for cold neutron stars. In this work, we use the HS(DD2) table in beta-equilibrium and at $T = 0.1$ MeV, which is cold on nuclear scale and therefore comparable to $T = 0$.

2.2 Quark Matter

Quark matter is described by the simple, generic constant speed of sound (CSS) EOS [3]

$$\epsilon_{\mathrm{CSS}}(p) = c_{\mathrm{QM}}^{-2}(p - p_0), \quad (1)$$

where ϵ_{CSS} denotes the energy density of the quark matter, p the pressure, p_0 the pressure where $\epsilon_{\mathrm{CSS}} = 0$ and c_{QM} the speed of sound of quark matter.

2.3 Hybrid EOS

To connect the hadronic phase described by the HS(DD2) EOS to the quark phase described by the CSS EOS, a Maxwell construction is applied. This implies that local charge neutrality is assumed. At the phase transition point pressure, temperature and baryon chemical equilibrium is found and no phase coexistence region is present in cold compact stars. The final form of the hybrid EOS is formulated as

$$\epsilon(p) = \begin{cases} \epsilon^{\mathrm{hadronic}}(p) & p \leq p_{\mathrm{trans}} \\ \epsilon^{\mathrm{hadronic}}(p_{\mathrm{trans}}) + & \\ \Delta\epsilon + c_{\mathrm{QM}}^{-2}(p - p_{\mathrm{trans}}) & p > p_{\mathrm{trans}} \ . \end{cases} \quad (2)$$

p_{trans} denotes the pressure at the phase transition point and $\Delta\epsilon = \epsilon_{\mathrm{quark}} - \epsilon_{\mathrm{hadronic}}$ the discontinuity in the energy density between the quark and hadronic phase which is a result of the Maxwell construction.

3. Parameter Scan

To analyze hybrid stars, two information are particularly relevant: the maximum mass configuration and the type of hybrid star. The former is determined by solving the Tolman-Oppenheimer-Volkov equations. The latter is identified by classifying the mass-radius curve into four different cases (A,B,C,D), as introduced by Alford et al. in [3]. Criteria are the stability at the onset of quark matter and if there is a so-called "third family" branch present (Note: White dwarfs are considered as the first family and neutron stars as the second family.). Fig. 1 shows the four cases: In case A ("Absent") the stable configurations consist of pure hadronic matter. In case C ("Connected") there are additionally stable hybrid configurations up to the maximum mass. Case D ("Disconnected") and B ("Both") have an additional third family branch. Up to the first maximum, case D corresponds to case A and case B corresponds to case C. The phase transition applied in Eq. 2 depends on three variables: p_{trans}, $\Delta\epsilon$ and c_{QM}. We fix the speed of sound to $c_{\mathrm{QM}}^2 = 1/3$. This value corresponds to non- or weakly interacting massless quarks. To systematically analyze hybrid stars, we vary p_{trans} from 1 MeV to 800 MeV and $\Delta\epsilon/\epsilon_{\mathrm{trans}} = [0, 1.3]$, 80 times each. The results are shown in Fig. 2. The colored dots indicate the calculated configurations and distinguish the four hybrid star cases. The lines in blue show the maximum mass contour lines. The thick black dashed line shows the analytic criterion from Seidov [6]. Above this line neutron stars are unstable at the onset of quark matter, below they are stable.

4. Results

The results shown in Fig. 2 are in good agreement with Alford et al.'s work published in [3, 7]. The general distribution of the cases A, B, C, and D is almost identical. The choice of the hadronic EOS seems to have very little impact on their distribution in the $p_{\mathrm{trans}}/\epsilon_{\mathrm{trans}}$ vs. $\Delta\epsilon/\epsilon_{\mathrm{trans}}$ plot. The mass contour lines show bigger differences. Especially the maximum mass of the chosen hadronic EOS leads to differences in their arrangement. In [7], Alford et al. analyzed a rather stiff hadronic EOS (DBHF), i.e. with a high maximum mass of 2.31 $\mathrm{M}_{\odot}$, and a soft hadronic EOS (BHF), i.e. with a lower maximum mass of 2.03 $\mathrm{M}_{\odot}$. They concluded that the softer EOS the more phase-transition

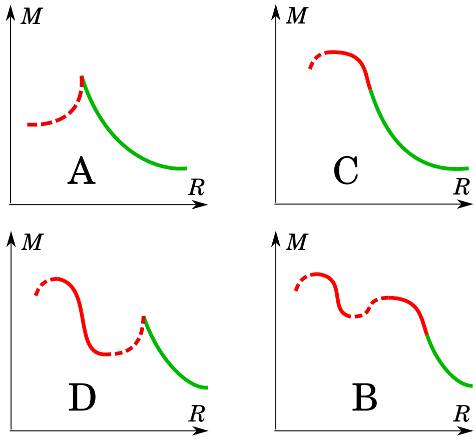

Fig. 1. Classification of the mass-radius curves into four different cases (A,B,C,D). Figure is based on Fig. 2 in [3]. The green line shows the stable hadronic stars, the solid red line the stable hybrid stars and the dashed red line the unstable hybrid stars.

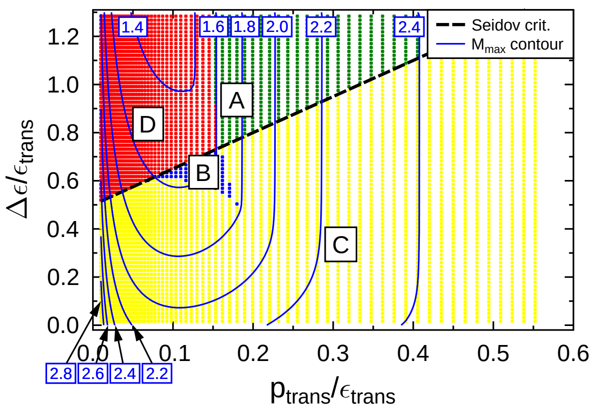

Fig. 2. Calculated hybrid star configurations, colored to distinguish the four cases (A,B,C,D). The lines in blue show the maximum mass contour lines. The thick black dashed line shows the analytic criterion from Seidov [6].

parameters are excluded due to the 2 $M_\odot$ constraint. HS(DD2) is slightly stiffer than DBHF. The 2 $M_\odot$ mass contour line of Fig. 2 is comparable to the 1.95 $M_\odot$ line of Fig. 5 in [7]. At low transition pressure, slightly more phase-transition parameters are allowed using HS(DD2) than using DBHF. HS(DD2) is also favorable compared to DBHF and BHF when looking for 2 $M_\odot$ hybrid stars with a third family. A more detailed comparison could be done on a logarithmic scale. Still, the overall features remain the same: Masses above the maximum mass of the hadronic EOS are possible at low $p_{trans}/\epsilon_{trans}$ and $\Delta\epsilon/\epsilon_{trans}$. Such hybrid stars contain almost only quark matter and just little hadronic matter. Hybrid stars with masses above 2 $M_\odot$ that show a third family in their mass-radius curve are found at low $p_{trans}/\epsilon_{trans}$ and moderate $\Delta\epsilon/\epsilon_{trans}$.

5. Summary and Conclusions

We performed a parameter scan applying the method introduced by Alford et al. in [3] but using the state-of-the-art supernova EOS HS(DD2). Our results are in good agreement with already published other parameter scans. Using HS(DD2) for the hadronic EOS shows that there is still a good part of the parameter space (at low densities) where quark matter can appear in hybrid stars while the 2 $M_\odot$ maximum mass constraint is still fulfilled. These calculations enable us to make further steps towards generating a new hybrid supernova EOS. In [8], we restrict an extended parameter scan using HS(DD2) EOS to a small region interesting for supernova simulations. We also address the problem of reconfinement and hyperons in our parameter scan and show its influence on the maximum mass.

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