Exploring Neutron Star Properties: Effect of Dark Matter and Magnetic Field

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Introduction

In astrophysics, the study of magnetars and pulsars, renowned as highly magnetized neutron stars, has garnered considerable attention in the recent years. These enigmatic celestial entities boast magnetic fields of astonishing strength, reaching levels on the order of $10^{17} - 10^{18}$ G, surpassing conventional neutron stars by several orders of magnitude. Such extreme magnetic conditions are unattainable in terrestrial laboratories, rendering pulsars and magnetars extraterrestrial laboratories for the exploration and advancement of physical theories.

Furthermore, with the majority of the universe's matter being dark matter (DM), neutron stars, due to their compact and dense nature, have served as crucial tools in unraveling the particle nature of DM and its scattering cross sections [1]. The presence of DM admixed with neutron stars can significantly alter their observables, such as mass-radius profiles, tidal deformability and luminosity, thus offering an indirect means of probing the DM properties [2]. While extensive research has been conducted in recent decades on DM-admixed neutron stars, the specific influence of DM on highly magnetized neutron stars remains an uncharted territory. In this study, we undertake an investigation into the unexplored interplay between DM and pure hadronic magnetized neutron stars.

Formalism

We employ the formalism for magnetized neutron stars outlined in reference [3], along with the effective relativistic mean field (E-RMF) model to describe nuclear interactions. Notably, this theory has been recently applied to investigate neutron stars with DM admixtures. For simulating the interaction between DM and the neutron star, we adopt the Neutralino as our DM candidate, classified as a Weakly Interacting Massive Particle (WIMP). We treat DM in a manner analogous to a neutron, treating it as a fermion with no electric charge. The interacting Lagrangian is written as [2]:

$$\begin{aligned}\mathcal{L}_{\rm DM} &= \bar{\chi}\Big[i\gamma^{\mu}\partial_{\mu} - M_{\chi} + yh\Big]\chi + \frac{1}{2}\partial_{\mu}h\partial^{\mu}h \\ &- \frac{1}{2}M_h^2 h^2 + \frac{fM}{v}\bar{\psi}h\psi, \qquad (1)\end{aligned}$$

The wave functions ψ and χ represent baryons and DM, respectively. In this context, we adopt specific values for the DM-Higgs coupling (y), the proton-Higgs form factor (f), and the vacuum value of the Higgs field (v), which are set at 0.07, 0.35, and 246 GeV, respectively, as previously discussed in Ref. [2].

Results and Discussions

For calculating the EoS of the NS, we use the IOPB-I E-RMF force in this work [4]. The IOPB-I parameter set reproduces the maximum mass from massive pulsars such as PSR J0740+6620, which estimate that the neutron star mass should be greater than 2 $M_\odot$ ($M = 2.14^{+0.10}_{-0.09}$ $M_\odot$) [5]). Figure 1 displays the equations of state (EOSs) for magnetized

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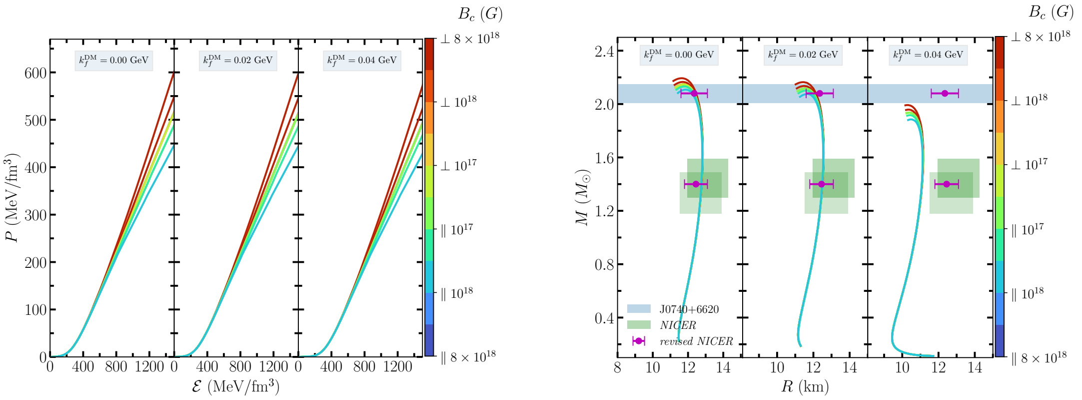

(a)

(b)

FIG. 1: (a)The EoS of the DM admixed NS with DM having Fermi momenta 0.00, 0.02, and 0.04 GeV and (b) the associated mass-radius profile.

neutron stars incorporating DM admixture, showcasing their dependence on the strength of the magnetic field (MF) for various DM fractions. These EOSs reveal an increase in stiffness or softness concerning the perpendicular (⊥) and parallel (∥) pressure components. Additionally, the presence of DM introduces a further softening effect on the EOSs, with the extent of softness primarily contingent on the amount of DM content within the neutron star.

The mass-radius ($M-R$) relationships are determined using the TOV equations over a range of central densities, as illustrated in Figure 1. The maximum mass and its corresponding radius exhibit a decrease when considering the parallel pressure component ($P_{\|}$), while the opposite trend is observed for the perpendicular pressure component ($P_{\perp}$). Furthermore, the inclusion of DM also leads to a reduction in the magnitude of both the mass (M) and the radius (R), which depends on the proportion of DM within the star. After the inclusion of both magnetic fields (MF) and DM, the maximum mass and its corresponding radius decrease by approximately 4-5%. For values of $k_f^{\mathrm{DM}} = 0.00$ and 0.02 GeV, only the parallel pressure components satisfy all the constraints imposed by Cromartie et al., pulsar observations, and NICER data. However, when $k_f^{\mathrm{DM}} = 0.04$ GeV, none of these constraints are met for the IOPB-I set. Consequently, this study highlights the potential for constraining the percentage of DM and the strength of the MF using a variety of observational data. This analysis reveals that the EOS and the mass-radius profile of DM-mixed magnetized neutron stars are influenced by two competing mechanisms: stiffening (or softening) due to perpendicular (or parallel) pressure components, and the softening caused by the increased DM content.

Acknowledgments

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