The population of highly magnetized neutron stars

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Abstract. In this work, we study the effects of strong magnetic field configurations on the population of neutron stars. The stellar matter is described within a relativistic mean field formalism which considers many-body force contributions in the scalar couplings. We choose the parametrization of the model that reproduces nuclear matter properties at saturation and also describes massive hyperon stars. Hadronic matter is modeled at zero temperature, in beta-equilibrium, charge neutral and populated by the baryonic octet, electrons and muons. Magnetic effects are taken into account in the structure of stars by the solution of the Einstein-Maxwell equations with the assumption of a poloidal magnetic field distribution. Our results show that magnetic neutron stars are populated essentially by nucleons and leptons, due to the fact that strong magnetic fields decrease the central density of stars and, hence, suppress the appearance of exotic particles.

1. Introduction

The topic of strong magnetic fields in neutron stars have been extensively studied in the literature. Magnetic field effects have been explored both on the equation of state \cite{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17} and on the structure of magnetic neutron stars \cite{18, 19, 20, 21, 22}, in order to identify their impact on the global properties of neutron stars, such as masses and radii. In particular, Refs. \cite{21, 22} have shown that magnetic effects in the equation of state are not strongly significant for the determination of global properties of stars (i.e., mass and radius), although magnetic field dependence on microscopic processes as neutrino emission and consequently the cooling are still important \cite{23}.

Another relevant effect of strong magnetic fields in neutron stars is their equatorial radius enhancement and the consequent decrease of the central baryon densities \cite{22}. Such effect can have a severe impact on the population of highly magnetized neutron stars. The decrease of the central chemical potential, related to the baryon density, can prevent the appearance of phase transitions \cite{22, 24} as well as the existence of exotic degrees of freedom. In this work, we show for a particular parametrization of the many-body forces model (MBF model) that the hyperon population of neutron stars is completely suppressed in the presence of central magnetic fields $B_c \sim 10^{18}$ G.

2. Hadronic Model

In order to describe hadronic matter inside magnetic stars, we make use of a many-body forces model (MBF model) \cite{25}, which is a relativistic mean field model that takes into account
nonlinear meson-meson contributions in the scalar interactions. The lagrangian density of the MBF model reads [25]:

\[
\mathcal{L} = \sum_b \bar{\psi}_b \left[ \gamma_\mu (i\partial^\mu - g_{\omega_b} \omega^\mu - g_{\phi_b} \phi^\mu - g_{\delta_b} I^\mu_3) - m_{b}\right] \psi_b + \sum_l \bar{\psi}_l \gamma_\mu (i\partial^\mu - m_l) \psi_l \\
+ \left( \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2 \right) + \frac{1}{2} \left( -\frac{1}{2} \omega_{\mu\nu} \omega^{\mu\nu} + m_\omega^2 \omega_{\mu\nu} \omega^{\mu\nu} \right) + \frac{1}{2} \left( -\frac{1}{2} \phi_{\mu\nu} \phi^{\mu\nu} + m_\phi^2 \phi_{\mu\nu} \phi^{\mu\nu} \right) + \frac{1}{2} \left( -\frac{1}{2} \delta_{\mu\nu} \delta^{\mu\nu} - m_\delta^2 \delta^2 \right),
\]

where the indices \( b \) and \( l \) denote the degrees of freedom of baryons (\( p^+, n, \Lambda, \Sigma^+, \Sigma^0, \Sigma^-, \Xi^0, \Xi^- \)) and leptons (\( e^-, \mu^- \)), respectively. The first line represents the Dirac lagrangian for baryons and leptons, respectively. The second line presents the lagrangian densities of the scalar-isoscalar \( \sigma \) field and the vector-isoscalar \( \omega \) and \( \phi \) fields, which reproduce the attractive and repulsive features of nuclear interaction. The isovector fields \( \delta \) (scalar) and \( g \) (vector) are introduced in the third line, and are responsible for the description of isospin asymmetry present in neutron stars. The inclusion of the \( \phi \) allows for a more accurate description of the hyperon-hyperon interaction. In this work we do not include the \( \sigma^* \) meson in order to focus on massive hyperon stars (for more results of the MBF model and the inclusion of the \( \sigma^* \) meson, see Ref. [25]).

The many-body forces contributions are introduced in the effective couplings of the scalar mesons:

\[
g_{b}^* = \left( 1 + \frac{g_{\omega_b} \o + g_{\delta_b} I_{3b}}{\zeta m_b} \right)^{-\zeta} g_{b}, \quad g_{b}^* = \left( 1 + \frac{g_{\omega_b} \o + g_{\delta_b} I_{3b}}{\zeta m_b} \right)^{-\zeta} g_{b}, \quad (2)
\]

making them no longer constants, but dependent on the scalar fields. Consequently, the effective baryon mass is also affected by many-body contributions as: \( m_{b}^{*} = m_{b} - g_{b} \o - g_{b} I_{3b} \). The parameter \( \zeta \) regulates the intensity of the nonlinear contributions from the scalar fields, which are interpreted as higher order meson-meson interactions contributions.

In order to describe massive hyperon stars, we use the parametrization \( \zeta = 0.040 \) that reproduces a binding energy per nucleon \( B/A = -15.75 \text{MeV} \) and a saturation density \( \rho_0 = 0.15 \text{fm}^{-3} \). Nuclear matter properties values at saturation for this choice of parameters are: effective mass of the nucleon \( m_n^* = 0.66 m_n \), compressibility \( K_0 = 297 \text{MeV} \), symmetry energy \( J_0 = 32 \text{MeV} \) and slope of the symmetry energy \( L_0 = 97 \text{MeV} \) [25]. Also, we use the spin-flavor SU(6) symmetry in order to define the hyperon couplings with the \( \omega, \phi, g \) and \( \delta \) fields [26, 27], and fix the hyperon potentials depths \( U^N_A = -28 \text{MeV} \), \( U^N_\Sigma = +30 \text{MeV} \) and \( U^N_\Xi = -18 \text{MeV} \) to obtain their coupling with the \( \sigma \) field.

3. Structure of magnetic stars

In order to describe the structure of magnetic neutron stars, we solve the Einstein-Maxwell equations system. In particular, we use the open source LORENE C++ library for numerical relativity developed by Bonazzola et al. [18, 19].

This formalism solves the Einstein’s equations coupled to the Maxwell’s equations for an axisymmetric metric using the 3+1 decomposition, which is a typical tool for numerical relativity. The system of equations is solved under the assumptions of meridional currents absence, infinite conductivity, magnetostatic equilibrium (from momentum and energy conservation) and for a poloidal magnetic field distribution. As the electromagnetic tensor fulfills the homogeneous Maxwell equations, only the Maxwell-Gauss and Maxwell-Ampère equations are left to be solved. For more details on the formalism, see Refs. [18, 19, 21, 22].

The formalism used in this work does not include the dynamics that would ultimately give rise to a magnetic field in the stars. For this reason, the magnetic field is generated by a current,
which is obtained from the EoS together with a current function \( j_0 \), which is introduced as a parameter. It has been shown in previous works that magnetic effects on the equation of state do not play a significant role on the determination of macroscopic properties of highly magnetized neutron stars \[21, 22\] and in this work, for this reason, we do not include such effects on the equation of state of the MBF model.

4. Maximum mass stars population

Strong magnetic fields have a very large impact on the population of neutron stars. First, the Lorentz force in magnetic stars acts against gravity, increasing the radius of stars and, consequently, reducing substantially their central density (and respective central baryon chemical potential). This can be seen in Fig. 1, in which the central density of a \( M_B = 2.2 \, M_\odot \) baryon mass star is shown as function of different choices of the current function \( j_0 \), i.e. for different magnetic field distributions.

We can now turn our attention to the maximum gravitational mass stars generated with our EoS including or not magnetic fields. Fig. 2 shows the particle population as a function of the radius for the non magnetic star, which is spherical and has a gravitational mass \( M_G = 2.15 \, M_\odot \) and central density \( \rho_c = 0.86 \, \text{fm}^{-3} \). The population is dominated by \( n \), \( \Lambda \) and \( \Xi^- \) particles in the inner region, due to the high densities reached at the stellar core \[25\].

Fig. 3 shows the population for the magnetic star that has a gravitational mass \( M_G = 2.22 \, M_\odot \) and the central density \( \rho_c = 0.70 \, \text{fm}^{-3} \). This is the maximum gravitational mass star for a magnetic configuration given by a current function \( j_0 = 3.5 \times 10^{15} \, \text{A/m}^2 \), which describes the strongest magnetic field distribution allowed by the code for the MBF model, with surface \( B_s = 3.8 \times 10^{17} \, \text{G} \) and central \( B_c = 1.1 \times 10^{18} \, \text{G} \) magnetic fields values. The particle population for the magnetic case is shown as a function of the polar radius of the star, but the results are qualitatively the same for the equatorial direction. It can be seen that, in case of central
magnetic fields of the order $\sim 10^{18}$ G, the hyperon population is completely suppressed.

The decrease of strangeness at the core of magnetic stars is directly caused by the decrease of their central density. In such stars, the central region does not provide enough energy to reach the hyperons threshold of appearance. Similar results have already been discussed in the literature for highly magnetized hybrid stars, proving that strong magnetic fields can also prevent the occurrence of phase transitions in such objects [22, 24]. Furthermore, although not investigated in this work, the microscopic effects of Landau quantization in the EoS also shifts the threshold of the appearance of hyperons to higher densities due to the extra magnetic contribution to the particles energy levels [2, 7, 28].

5. Discussion

Strong magnetic fields in neutron stars have long been studied, usually focusing on their effects on the global properties of stars, such as masses, radii and deformation. In this work, we have applied a formalism that allows for describing consistently the structure of magnetic neutron stars, taking into account their deformation as well as solving the Einstein-Maxwell equations system for determining their structure (instead of using the Tolman-Oppenheimer-Volkoff spherical solutions). The hadronic matter interaction inside the stars was described by the MBF model, which considers many-body forces contributions in the effective coupling of scalar mesons. The matter was modeled to be at zero temperature, charge neutral, in beta-equilibrium and populated by nucleons, hyperons and leptons (for the non magnetic case).

We have shown that in the presence of strong magnetic field distributions, the central density of stars decreases due to the Lorentz force. This has the direct impact of decreasing the strangeness fraction at their core. Comparing the case of the maximum gravitational mass for the scenarios of a non magnetic star and for the highest magnetic field configuration allowed by the code, we find that central magnetic fields as strong as $\sim 10^{18}$ G supress completely the hyperon population of magnetic neutron stars, similarly to previous results for phase transitions in hybrid stars. These results imply that, as magnetic field strengths decay over time, a repopulation mechanism is driven inside stars, similarly to the one investigated for slowing down pulsars [29]. Such results are important for the detection of signals for exotic matter (hyperons, delta...
isobars, quark matter) inside magnetic neutron stars such as their cooling, tidal deformation and gravitational wave emissions. A similar work considering other parametrizations of the MBF model and performing a similar population investigation but for stars with the same baryonic mass is already in preparation.

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