Hyperon Stars in Strong Magnetic Fields

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1 Introduction

We investigate the effects of strong magnetic fields on the properties of hyperon stars. The matter is described by a hadronic model with parametric coupling. The matter is considered to be at zero temperature, charge neutral, beta-equilibrated, containing the baryonic octet, electrons and muons. The charged particles have their orbital motions Landau-quantized in the presence of strong magnetic fields (SMF). Two parametrizations of a chemical potential dependent static magnetic field are considered, reaching $1 - 2 \times 10^{18} G$ in the center of the star. Finally, the Tolman-Oppenheimer-Volkov (TOV) equations are solved to obtain the mass-radius relation and population of the stars.

2 The Model

The matter is described in a relativistic mean field formalism. We use a parametric coupling effective model that considers genuine many-body forces simulated by non-linear self-couplings interaction terms involving the scalar-isoscalar $\sigma$-meson field [1].
The Lagrangian density of our model is defined as:

\[
\mathcal{L} = \sum_b \bar{\psi}_b (i\gamma_\mu \partial^\mu + q_\epsilon \gamma_\mu A^\mu - m_b) \psi_b + \sum_l \bar{\psi}_l (i\gamma_\mu \partial^\mu + q_\epsilon \gamma_\mu A^\mu - m_l) \psi_l \\
+ \frac{1}{2} (\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2) + \left( -\frac{1}{4} \omega_\mu \omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^{\mu} \right) + \left( -\frac{1}{4} g_{\mu\nu} \cdot \mathbf{g}^{\mu\nu} + \frac{1}{2} m_\mathbf{g}^2 \mathbf{g} \cdot \mathbf{g} \right) \\
- \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \sum_b \left( g_{\sigma b}^* \bar{\psi}_b \gamma_\mu \sigma - g_{\omega b} \bar{\psi}_b \gamma_\mu \omega^{\mu} \right) - \frac{1}{2} g_{\tau b} \bar{\psi}_b \gamma_\mu \psi_b \tau \cdot \mathbf{g}
\]

where the hadron-meson coupling is parameterized by: 

\[
g_{\sigma b}^* \equiv \left( 1 + \frac{g_0 \sigma}{\lambda m_b} \right)^{-\lambda} g_{\sigma b}.
\]

The effective mass dependence on \(\lambda\) is given by [1]:

\[
m_b^* = m_b - \frac{g_{\sigma b} \sigma_0}{\left( 1 + \frac{g_0 \sigma}{\lambda m_b} \right)^{\lambda}}.
\]

Defining the meson-hyperon couplings as \(g_{\eta B} = \chi_{\eta B} g_{\eta N}\) for \(\eta = \sigma, \omega, \varrho\), we consider a model based on experimental analysis of hypernucleus data. This model considers that all hyperon-meson coupling intensities are the same as that of the \(\Lambda\)-hyperon: \(\chi_{\sigma B} = \chi_{\sigma \Lambda}\), \(\chi_{\omega B} = \chi_{\omega \Lambda}\), \(\chi_{\varrho B} = 0\). The \(\Lambda\)-hypernucleus binding energy is given by [2]:

\[
(B/A)_\Lambda = \chi_{\omega B} (g_{\omega N} \omega_0) + \chi_{\sigma B} (m_\Lambda - m_\Lambda),
\]

and, in this work, we use \((B/A)_\Lambda = -28 \text{ MeV}\) at saturation density and \(\chi_{\sigma \Lambda} = 0.75\).

**Landau Quantization:** The charged particles orbital motion quantization generates the energy spectra: \(E_{\nu, i} = \sqrt{k_{z i}^2 + m_i^2 + 2\nu q_\epsilon |B|}\), where: \(m_i = m_b^*\), for baryons and \(m_i = m_l\), for leptons.

We enumerate the Landau levels by \(\nu\), which are double degenerated except for the fundamental state. The largest \(\nu\) value for which the \(k_{F}^2 > 0\) corresponds to \(\nu_{\text{max}}^b = (\mu_b^*)^2 - (m_b^*)^2/2q_\epsilon |B|\) and \(\nu_{\text{max}}^l = (\mu_l^*)^2 - (m_l^*)^2/2q_\epsilon |B|\), for baryons and leptons, respectively. Due to interactions, effective chemical potentials for baryons are considered. The chemical potentials are: \(\mu_b^* = E_{F b}^b + g_{\omega b} \omega_0 + g_{\sigma b} \sigma_0, m_0, \rho_0\) for baryons, and \(\mu_l = E_{F l}^l\) for leptons. The fermi energies are: \(E_{F b}^b = \sqrt{(k_{F b, \nu})^2 + (m_b^*)^2}\) and \(E_{F l}^l = \sqrt{(k_{F l, \nu})^2 + (m_l^*)^2}\).

The magnetic field modified mass and fermi momentum are defined for baryons and leptons as:

\[
\overline{m_{b, \nu}^2} = (m_b^*)^2 + 2\nu q_\epsilon |B|, \quad k_{F b, \nu} = \sqrt{(\mu_b^*)^2 - (\overline{m_{b, \nu}^2})^2},
\]

\[
\overline{m_{l, \nu}^2} = m_l^2 + 2\nu q_\epsilon |B|, \quad k_{F l, \nu} = \sqrt{(\mu_l^*)^2 - (\overline{m_{l, \nu}^2})^2}.
\]
The equation of state of a magnetized neutron star matter (\(\varepsilon_{mag}, P_{mag}\)) was already calculated by [4]. The difference in the calculation for our model is that we have a different effective mass expression, which modifies the results for chemical equilibrium.

Considering the pressure isotropy [5, 6], the EoS with all contributions are:

\[
\varepsilon = \sum_{B,l} \varepsilon_{mag} + \frac{B^2}{2}, \quad P_{\parallel} = \sum_{b,l} P_{mag} - \frac{B^2}{2}, \quad P_{\perp} = \sum_{b,l} P_{mag} + \frac{B^2}{2} - BM. 
\]

The magnetization is calculated as: \(M = \partial P_{mag}/\partial B\).

In this work, we use a density dependent magnetic field. We consider a magnetic field with the following baryonic chemical potential dependence [3]:

\[
B(\mu) = B_{surf} + B_c [1 - \exp (-b (\mu_n - 938)^a)].
\]  

Figure 1: EoS dependence with \(B\) for different parameters: \(\lambda = 0.06; 0.10; 0.14\) \((m^*/m_N = 0.70; 0.75; 0.78\ MeV)\)

\(B_{surf}\) and \(B_c\) correspond to the magnetic field at the surface of the star, \(B_{surf} = 10^{15}\ G\), and at very high baryon chemical potential, which we vary. The parameters \(a\) and \(b\) tell how fast the magnetic field chemical potential dependence is \((a = 2.5; \quad b = 4.35 \times 10^{-7})\).

\section{3 \ Results and Conclusion}

When all contributions are considered, the total EoS gets stiffer for higher magnetic fields, Fig[1] due mainly to the pure magnetic field contribution. As a consequence, the mass-radius relation permits higher maximum masses for hyperon stars. From uncertainties of nuclear matter properties at saturation and our choice of hyperonic coupling scheme, the TOV relations [7] allow us to describe a magnetic hyperon star...
Figure 3: Particles population, $\lambda = 0.06$, $m^*/m_N = 0.70$ and $B = 0 G$. Figure 4: Particles population, $\lambda = 0.06$, $m^*/m_N = 0.70$ and $B = 4 \times 10^{18} G$.

with $2.03M_\odot$, as shown in Fig 2. We show in Fig 3, 4 that the presence of a strong magnetic field supresses the hyperon population, which is in agreement with [4].

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