The role of magnetic fields in hyperon stars

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Abstract. We investigate the effects of strong magnetic fields (SMF) on the properties of neutron stars that have hyperons in their composition. The matter is described by a hadronic model in which a parameterized and derivative coupling between hadrons and mesons is considered. We study the magnetic effects on the equation of state (EoS) from Landau quantization, assuming a density dependent static magnetic field that reaches $10^{19}\,G$ in the center of the star. The Tolman-Oppenheimer-Volkoff (TOV) equations are solved in order to show the dependence of the mass-radius relation and population of hyperon stars on the central magnetic field and on different hyperon coupling schemes.

Keywords: neutron stars, equation of state, magnetic fields
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INTRODUCTION

The observation of compact objects with surface magnetic fields as strong as $10^{14}-10^{15}$ Gauss, denominated *magnetars*, has drawn the attention to the study of the EoS of hadronic matter in the presence of strong magnetic fields. In the interior of magnetars, the magnetic fields are expected to be even stronger, maybe reaching 10^{19} Gauss. We verify the effects of SMF in the observational properties of neutron stars describing magnetic hadronic matter in a new relativistic mean field formalism. Assuming the appearence of hyperon species in the system, we use different models to describe the meson-hyperon coupling.

MAGNETIC HADRONIC MODEL

We use a parametric coupling effective model that considers genuine many-body forces simulated by nonlinear self-couplings interaction terms involving the scalar-isoscalar σ-meson field [1]. The Lagrangian density of our model is defined as:

$$\mathscr{L} = \sum_b \bar{\psi}_b(i\gamma_\mu\partial^\mu + q_e\gamma_\mu A^\mu - m_b)\psi_b + \sum_l \bar{\psi}_l(i\gamma_\mu\partial^\mu + q_e\gamma_\mu A^\mu - m_l)\psi_l$$
$$+\frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) + \Big(-\frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu\Big) + \Big(-\frac{1}{4}\rho_{\mu\nu}\cdot\rho^{\mu\nu} + \frac{1}{2}m_\rho^2\rho_\mu\cdot\rho^\mu\Big)$$
$$-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \sum_b \big(g_{\sigma b}^*\bar{\psi}_B\psi_b\sigma - g_{\omega b}\bar{\psi}_B\gamma_\mu\psi_b\omega^\mu - \frac{1}{2}g_{\rho b}\bar{\psi}_b\gamma_\mu\psi_b\tau\cdot\rho^\mu\big), \tag{1}$$

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where b and l label, respectively, the baryon octet (n, p, Λ^0, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0) and lepton (e^-, μ^-) species. The eletromagnetic tensor is denominated by $F^{\mu\nu}$.

The hadron-meson coupling is parameterized by: $g^*_{\sigma b} \equiv \left(1 + \frac{g_\sigma \sigma}{\lambda m_b}\right)^{-\lambda} g_{\sigma b}$. The effective mass dependens on λ as: $m^*_b = m_b - g^*_{\sigma b}\sigma_0$. We constrain the λ parameter in order to describe the effective mass of the nucleon $m^*_N/m_N = 0.70\,MeV$ and compression modulus $K_0 = 262\,MeV$ [2] at saturation density. Also, we set the isovector coupling constant $g_\rho b$ to describe the symmetry energy coefficient $a_{sym} = 32.5MeV$. We emphasize that our model predicts the values of nuclear saturation properties in good agreement with literature with only one choice of parameter λ.

Defining the hyperon-meson couplings as $g_{\eta B} = \chi_{\eta B}\, g_{\eta N}$ for $\eta = \sigma, \omega, \rho$, we consider the three following models:

- **HYS(1)** [3]: is based on the different nature of hyperons with respect to nucleons.

$$\chi_{\sigma B} = \chi_{\omega B} = \chi_{\rho B} = \sqrt{2/3}; \tag{2}$$

- **HYS(2)** [4]: is based on the counting quark rule.

$$\begin{gathered} \chi_{\sigma\Lambda} = 2/3, \quad \chi_{\sigma\Sigma} = 2/3, \quad \chi_{\sigma\Xi} = 1/3, \\ \chi_{\omega\Lambda} = 2/3, \quad \chi_{\omega\Sigma} = 2/3, \quad \chi_{\omega\Xi} = 1/3, \\ \chi_{\rho\Lambda} = 0, \quad \chi_{\rho\Sigma} = 2, \quad \chi_{\rho\Xi} = 1; \end{gathered} \tag{3}$$

- **HYS(3)** [5, 6]: is based on experimental analysis of Λ-hypernucleous data.

$$\chi_{\sigma B} = \chi_{\sigma\Lambda}, \chi_{\omega B} = \chi_{\omega\Lambda}, \chi_{\rho B} = 0, \tag{4}$$

  where the binding energy is given by:
  $(B/A)_\Lambda = \chi_{\omega B}\,(g_{\omega N}\,\omega_0) + \chi_{\sigma B}\,(m^*_\Lambda - m_\Lambda) = -28\,MeV$, and $\chi_{\sigma\Lambda} = 0.75$.

In the presence of a magnetic field, the orbital motion of the charged particles is described by Landau quantization energy spectra. We calculate the EoS from the spatial and temporal contributions of the energy-momentum tensor of the system, following the solutions already calculated in the literature [7, 8], and also assuming an anisotropic pressure, as pointed by [9, 8]:

$$\varepsilon = \sum_{B,l} \varepsilon_{mag} + \frac{B^2}{2}, \quad P_\parallel = \sum_{b,l} P_{mag} - \frac{B^2}{2}, \quad P_\perp = \sum_{b,l} P_{mag} + \frac{B^2}{2} - B\mathscr{M}, \tag{5}$$

where the magnetization is calculated as $\mathscr{M} = \partial P_{mag}/\partial B$.

We assume a magnetic field with the following baryonic chemical potential dependence [10]:

$$B(\mu) = B_{surf} + B_c\left[1 - \exp\left(-b\,(\mu_n - 938)^a\right)\right], \tag{6}$$

where the parameters a and d determine how fast the magnetic field increases towards the center of the star. In this work, we use the parameterization: $a = 2.5$, $d = 4.35 \times 10^{-7}$, and a surface magnetic field of $B_{surf} = 10^{15}\,G$, proposed in previous works [11].

RESULTS AND CONCLUSIONS

Figure 1 shows that the EoS gets stiffer for higher central magnetic fields due mainly to the pure magnetic field contribution. Also, we find a $10^{19}\,G$ central magnetic field threshold, beyond which the pure magnetic field contribution is dominant. Although a more rigorous formalism is needed to describe the relativistic structure of magnetic neutron stars, it is possible to have an approximated idea of the magnetic effects on the mass of a hyperon star using the perpendicular pressure in the solution of the TOV equations [12, 13]. Applying three different hyperonic coupling schemes, our model describes a magnetic hyperon star with $2.52M_{\odot}$ and a non-magnetic hyperon star with $1.97M_{\odot}$ for the HYS(3) model. We verify that the HYS(1) and HYS(2) models shall not be considered in the description of hyperon stars in further calculations, since they cannot describe a non magnetic star that fits the observational data [14]. However, our results show that the hyperon population still cannot be discarded in neutron stars.

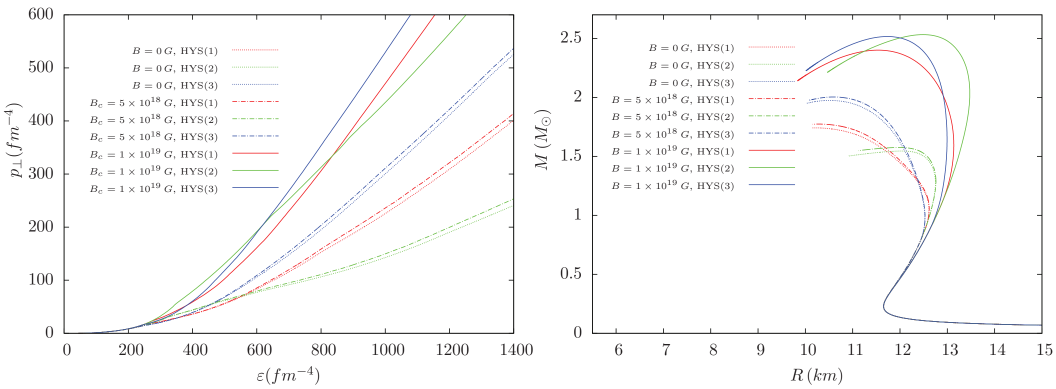

FIGURE 1. EoS and mass-radius diagram for different central magnetic fields B_c, for a saturation density of $\rho_0 = 0.17 fm^{-3}$, binding energy $E_{binding} = -16.0MeV$ and $\lambda = 0.06$. The x and y axis are the energy density and pressure, on left panel and the radius and mass, on the right.

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