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Study of Pulsars and Magnetars

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In the present work, we study some of the physical characteristics of neutron stars, especially the mass-radius relation and chemical compositions of the star within a relativistic model subject to a strong magnetic field. To study the influence of the magnetic field in the stellar interior, we consider altogether four solutions: two different values for the magnetic field to obtain a weak and a strong influence, and two configurations: a family of neutron stars formed only by protons, electrons and neutrons and another family formed by protons, electrons, neutrons, muons and hyperons. In both cases all the particles that constitutes the neutron star are in β equilibrium and the total net charge is zero.

Keywords:
Neutron stars, pulsars, magnetars, compact objects.

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1. Introduction

In the pesent work we study a hadronic neutron star constituted by nucleons and hyperons and subject to a strong magnetic field. The presence of hyperons is justifiable because the constituents of neutron stars are fermions. Due to the Pauli Principle, as the baryon density increases, so do the Fermi momentum and the Fermi energy until the Fermi energy exceeds the masses of the heavier baryons [1]. On the other hand, soft gamma-ray repeaters and anomalous X-ray pulsars can be explained by the existence of magnetars [2], which are neutron stars with very strong magnetic fields on their surface. Although the magnetic field of magnetars are not expected to do exceed $10^{15}G$, it is well-accepted in the literature that the magnetic field in their core can reach values greater than $10^{18}G$ [3, 4]. Due to the large densities in the neutron star interior, we do not expect any significant influence of the magnetic field till it reaches values of $5.0 \times 10^{17}G$ [5, 6].

2. Formalism

The Lagrangian density of the non-linear Walecka model (NLWM) [5] reads:

$$\mathscr{L} = \sum_b \mathscr{L}_b + \sum_l \mathscr{L}_l + \mathscr{L}_m + \mathscr{L}_{\mathscr{B}}, \tag{2.1}$$

where b stands for the baryons, l for the leptons, m for the mesons and $\mathscr{B}$ for the electromagnetic field itself. The sum in b can run over the eight lighter baryons and in l the two lighter leptons. Explicitly, in a presence of a electromagnetic field we have [5, 6]:

$$\mathscr{L}_b = \bar{\Psi}_b[\gamma_u(i\partial^\mu - eA^\mu - g_{v,b}\omega^\mu - g_{\rho,b}I_{3b}\rho^\mu) - (M_b - g_{s,b}\sigma)]\Psi_b, \tag{2.2}$$

$$\mathscr{L}_l = \bar{\psi}_l[\gamma_u(i\partial^\mu - eA^\mu)] - m_l]\psi_l, \tag{2.3}$$

$$\mathscr{L}_m + \mathscr{L}_{\mathscr{B}} = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_s^2\sigma^2 + \frac{1}{2}m_v^2\omega_\mu\omega^\mu - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \tag{2.4}$$

$$+\frac{1}{2}m_\rho^2(\rho_\mu\rho^\mu) - \frac{1}{4}P_{\mu\nu}P^{\mu\nu} - \frac{1}{3!}\kappa\sigma^3 - \frac{1}{4!}\lambda\sigma^4 - \frac{1}{16\pi}F_{\mu\nu}F^{\mu\nu} \tag{2.5}$$

To obtain the equation of state (EoS) associated with the NLWM, we use a mean field approximation, where the meson fields are replaced by their expectation values, ie: $\sigma \to \langle\sigma\rangle = \sigma_0$, $\omega^\mu \to \delta_{0\mu}\langle\omega^\mu\rangle = \omega_0$ and $\rho^\mu \to \delta_{0\mu}\langle\rho^\mu\rangle = \rho_0$. In this work we use the GM1 parametrization [7], that can describe the most important properties of nuclear matter and reproduce neutron star properties which are consistent with those observed by astronomers.

The energy density of the system described by the above Lagrangian density reads:

$$\varepsilon = \sum_{ub}\varepsilon_b + \sum_{cb}\varepsilon_b + \sum_l \varepsilon_l + \sum_m \varepsilon_m + \frac{B^2}{8\pi}, \tag{2.6}$$

where ub stands for "uncharged baryons", cb for "charged baryons", l for leptons and m for mesons. They are given respectively by:

PoS(XXXIV BWNP)098

$$\varepsilon_{ub} = \frac{1}{\pi^2}\int_0^{k_f}\sqrt{M_b^{*2}+k^2}k^2dk, \tag{2.7}$$

$$\varepsilon_{cb} = \frac{|e|B}{2\pi^2}\sum_{\nu}^{\nu_{max}}\eta(\nu)\int_0^{k_f}\sqrt{M_b^{*2}+k_z^2+2\nu|e|B}dk_z, \tag{2.8}$$

$$\varepsilon_{l} = \frac{|e|B}{2\pi^2}\sum_{\nu}^{\nu_{max}}\eta(\nu)\int_0^{k_f}\sqrt{m_l^{2}+k_z^2+2\nu|e|B}dk_z, \tag{2.9}$$

$$\varepsilon_m = \frac{1}{2}m_s^2\sigma_0^2+\frac{1}{2}m_v^2\omega_0^2+\frac{1}{2}m_\rho^2\rho_0^2+\frac{1}{3!}\kappa\sigma_0^3+\frac{1}{4!}\lambda\sigma_0^4. \tag{2.10}$$

where ν is the Landau level (LL). The summation in ν terminates at ν_{max}, the largest value of the LL for which the square of the Fermi momenta of the particle is still positive [5], and

$$M_b^* = M_b - g_{s,b}\sigma_0, \tag{2.11}$$

is the baryon effective mass.

Now we impose β-equilibrium conditions and zero electric charge:

$$\mu_{b_i} = \mu_n - e_i\mu_e, \quad \mu_e = \mu_\mu, \quad \sum_b e_b n_b + \sum_l e_l n_l = 0 \tag{2.12}$$

where μ_{b_i} and e_i are the chemical potential and charge of the i-th baryon, and μ_n, μ_e and μ_μ are the chemical potential of the neutron, electron and muon respectively, n_b and n_l are the number density of the baryons and the leptons, and read:

$$n_{ub} = \frac{k_f^3}{3\pi^2}, \quad \text{for the uncharged baryons,} \tag{2.13}$$

$$n = \frac{|e|B}{2\pi^2}\sum_{\nu}^{\nu_{max}}k_f, \quad \text{for the charged baryons and leptons.} \tag{2.14}$$

To find the pressure, we use the second law of thermodynamics. It is given by:

$$p = \sum_i \mu_i n_i - \varepsilon + \frac{B^2}{8\pi}, \tag{2.15}$$

where the sum runs over all fermions. Note that the contribution from the electromagnetic field is taken into account in the calculation of the energy density and the pressure.

2.1 Density-dependent magnetic field

The magnetic field of the magnetars are expected to be of order of $10^{15}G$, but it can reach values larger than $10^{18}G$ in its core. To reproduce this behavior we use a density-dependent magnetic field given by [3, 8, 9]:

$$B(n) = B^{suf} + B_0\left[1 - exp\left\{-\beta\left(\frac{n}{n_0}\right)^{\alpha}\right\}\right], \tag{2.16}$$

where B^{suf} is the magnetic field on the surface of the neutron stars, taken as $10^{15}G$, n is the total number density, $n = \sum n_b$, n_0 is the nuclear saturation density given by $n_0 = 0.153 fm^{-3}$, B_0 is the magnetic field. The two free parameters are $\beta = -5.76 \cdot 10^{-3}$, and $\alpha = 3$. Now $B(n)$ replaces B in the term $B^2/8\pi$.

3. Results and Conclusions

We consider two families of neutron stars: one containing just protons, electrons and neutrons, which we call "Atomic Star" denoted by the letter A, and another containing protons, electrons, neutrons, muons and hyperons, that we call "Hyperonic Star" denoted by the letter H. In the results we also include the crust of neutron star through the BPS EoS [11]. We choose $2.2 \cdot 10^{17}G$ and $6.6 \cdot 10^{18}G$ magnetic field strenght to produce a weaker and a stronger influence.

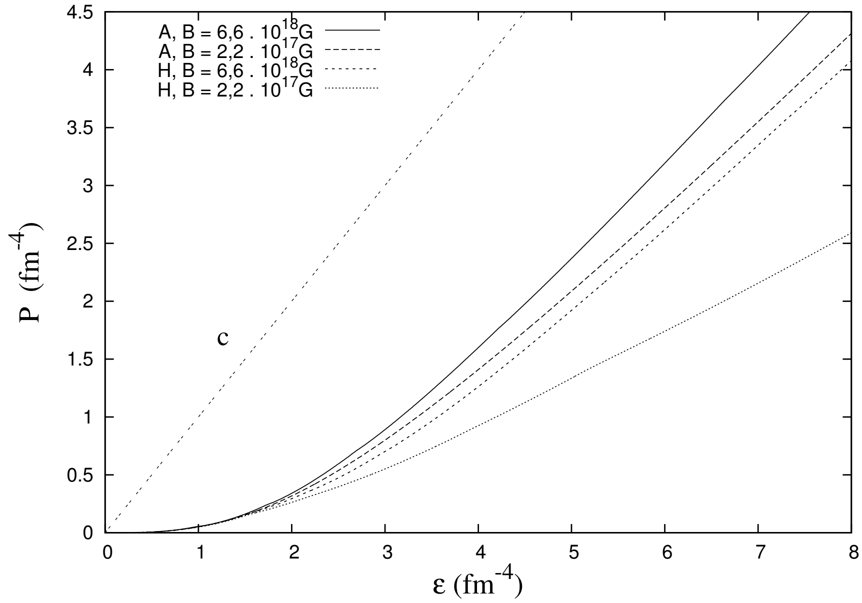

Figure 1: EoS for two atomic and two hyperonic stars obtained with different values of the magnetic field. The inclined straight line corresponds to the causal limit, for which $\varepsilon = p$.

As we can see from the figure 1, the presence of hyperons softens the EoS more than the influence of the magnetic field hardens it. No matter how strong is the magnetic field in the interior of the magnetar, the EoS of a atomic star is always stiffer than a hyperonic one. We can see also that all our EoS are causal (the "c" line is the causality limit).

In figures 2 and 3 we show how the fraction of particles $Y_i = n_i/n$, change with the density for a weak and a strong magnetic field. Under the influence of the weaker magnetic field, the particle population is always well behaved, while for stronger one many kinks appear due to the filling of the LL. This is because for a weak magnetic field a lot of Landau levels are occupied, but for a strong magnetic field, just a few of them are filled. For strong magnetic fields, the appearance of charged particles is favored at low densities due to their dependence on the magnetic field, as shown in eq. (2.14). One can notice that for hyperonic stars, at densities of the order of $0.8\ fm^{-3}$, the neutron is no longer the most important constituent. From this point, the Λ^0 hyperon dominates in the region of high densities.

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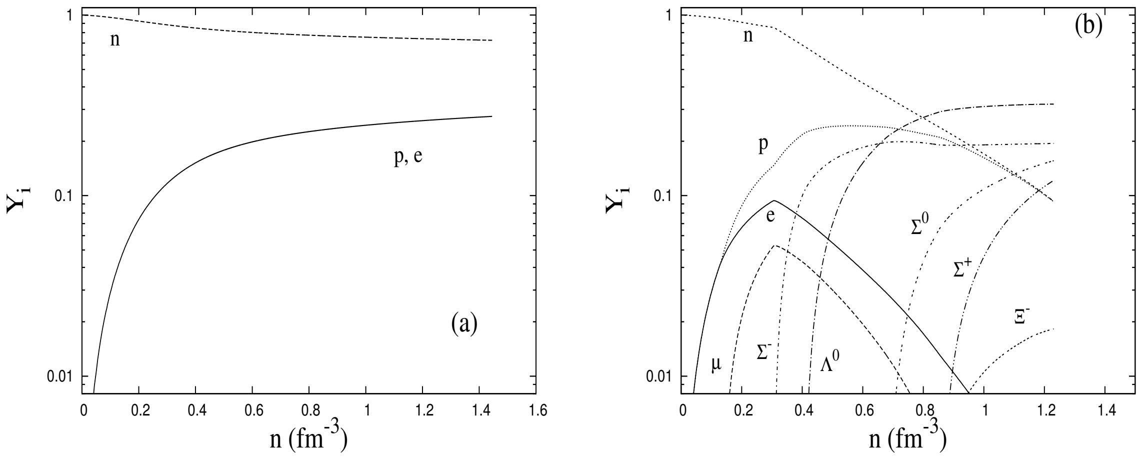

Figure 2: Fraction of particles Y_i as a function of the density for (a) atomic stars and (b) hyperonic stars for a magnetic field of 2.2 . $10^{17}G$

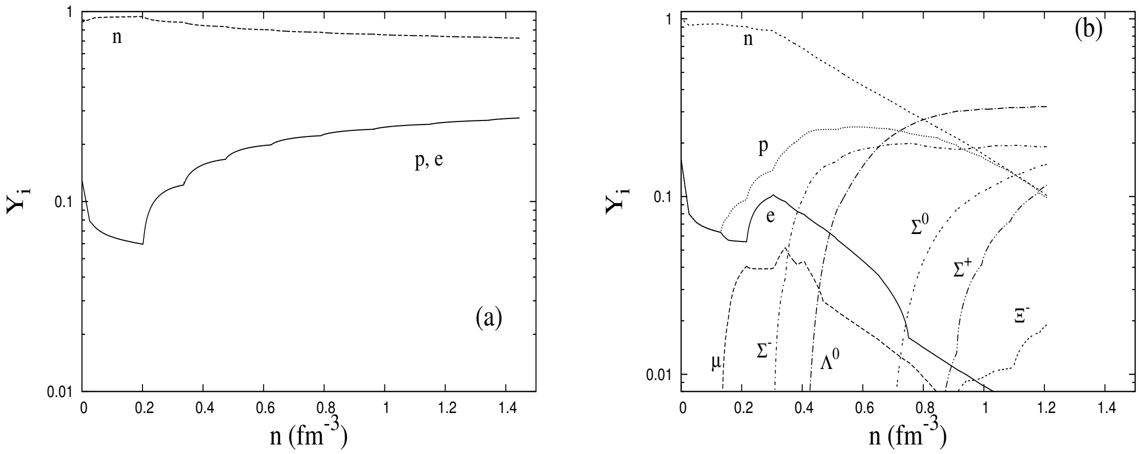

Figure 3: Fraction of particles Y_i as a function of the density for (a) atomic stars and (b) hyperonic stars for a magnetic field of 6.6 . $10^{18}G$

In order to validate our EoS, we have to solve the TOV equation and check if the results agree with observational constraints. The star masses cannot exceed the maximum theoretical neutron star mass of 3.2 solar masses [12]. The EoS has to be able to predict the 1.97 solar masses neutron star [13] and to be in agreement with the redshift measurements (z) of two neutron stars. A redshift of $z = 0.35$ has been obtained from the X-ray binary EXO0748-676 [14]. Another constraint is from the 1E 1207.4-5209 neutron star, with redshift values ranging from $z = 0.12$ to $z = 0.23$, [15]. Stars with central densities above that of the maximum mass stars are mechanically unstable [1].

Solving TOV equation for the four EoS discussed above we obtain the results presented in Table I .

	Max. Mass ($M_{\odot}$)	Radius (km)	n_c (fm^{-3})	B $\times 10^{18} (G)$
Atomic	2.50	12.30	0.701	6.6
Atomic	2.39	12.10	0.840	0.22
Hyperonic	2.28	11.82	0.796	6.6
Hyperonic	2.01	11.84	0.952	0.22

Table 1 : *Neutron stars properties computed from the four EoS used as input to the TOV equation. The maximum masses are given in units of solar masses, the radii in Km, the central densities in fm^{-3} and the magnetic fields in Gauss.*

The well known fact that the EoS of hyperonic stars are always softer than the EoS of atomic ones reflects in their maximum masses, as seen in Table 1. We also plot the TOV solution to compare the results in figure 4. In relation to the macroscopic properties of neutron stars, the magnetic field increases the maximum masses. This result is more evident in hyperonic stars than in atomic ones.

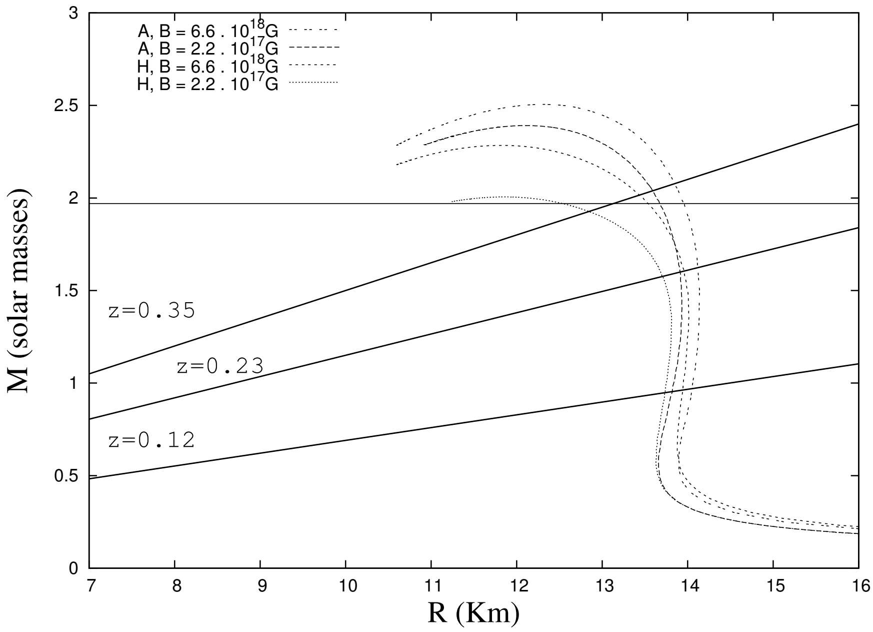

Figure 4: Mass-radius relation for two atomic and two hyperonic stars with different values of magnetic field. The straight lines are the observational constrains.

The inclined straight lines in fig. 4 are the constrains of the measured redshift while the horizontal one corresponds to the 1.97 $M_{\odot}$ pulsar. Every single dot in the curves is a possible neutron star. We can see that all our models are in agreement with the constrains proposed in [12, 13, 14, 15]. On the other hand, if we consider hyperons and muons in their interior, the maximum mass that they can reach is very close of the 1.97 $M_{\odot}$.

In this work we have shown that the main effect of strong magnetic fields is to increase the maximum mass of neutron stars as seen in [8, 9]. Moreover the macroscopic quantities we have obtained (maximum masses, radii) are only sensitive to magnetic fields stronger than $10^{18} G$. For magnetic fields as weak as $10^{17} G$ the macroscopic quantities computed from the TOV equation are very close to the ones obtained for zero magnetic field [1].

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References

[1] N. K. Glendenning: *Compact Stars*
Springer, New York 2000

[2] R. Duncan, C. Thompson, *The Soft gamma repeaters as very strongly magnetized neutron stars, Mon. Not. R. Astron. Soc.* **275** (255) 1995 .

[3] S. Pal, D. Bandyopadhyay, S. Chakrabarty, *Dense Nuclear Matter in Strong Magnetic Field, Phys. Rev. Lett.* **78** (2898) 1997 .

[4] S. Pal, D. Bandyopadhyay, S. Chakrabarty, *Strong magnetic field in a protoneutron star, J. Phys. G: Nucl. Part. Phys.* **25** (L117) 1999 .

[5] A. Rabhi, C. Providencia and J. Da Providencia, *Stellar matter with a strong magnetic field within density-dependent relativistic models, J. Phys. G: Nucl. Part. Phys.* **35** (125201) 2008 .

[6] A. Broderick, M. Prakash, J. M. Lattimer, *The Equation of State of Neutron Star Matter in Strong Magnetic Field, Astrophys. J.* **537** (351) 2000 .

[7] N. K. Glendenning, S. A. Moszkowski, *Reconciliation of neutron-star masses and binding of the* Λ *in hypernuclei, Phys. Rev. Lett.* **67** (2414) 1991 .

[8] A. Rabhi et al, *Quark-hadron phase transition in a neutron star under strong magnetic fields, J. Phys. G: Nucl. Part. Phys.* **36** (115204) 2009.

[9] D. P. Menezes et al, *Quark matter under strong magnetic fields in the su(3) Nambu-Jona-Lasinio model, Phys. Rev. C* **80** (065805) 2009 .

[10] J. R. Oppenheimer, G. M. Volkoff, *On Massive neutron cores, Phys. Rev.* **33** (374) 1939 .

[11] G. Baym, C. Pethick, P. Sutherland, *The Ground State of Matter at High Densities: Equation of State and Stellar Models , Astrophys. J.* **170** (299) 1971 .

[12] C. E. Rhoades, R. Ruffini, *Maximum Mass of a Neutron Star, Phys. Rev. Lett.* **32** (324) 1974 .

[13] P. B. Demorest et al, *Shapiro Delay Measurement of A Two-Solar Mass Neutron Star, Nature.* **467** (1081) 2010 .

[14] J. Cottam, F. Paerels, M. Mendez, *Gravitationally redshifted absorption lines in X-ray burst spectra of a neutron star, Nature* . **420** (51) 2002 .

[15] D. Sanwal et al.: *Discovery of Absorption Features in the X-ray Spectrum of an Isolated Neutron Star, Astrophys. J. Lett.* **574** (L61) 2002 .