Astroparticle Physics 38 (2012) 25–30

Contents lists available at SciVerse ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

QHD description of the instability in strongly magnetized neutron stars

Chung-Yeol Ryu [a], Myung-Ki Cheoun [a,*], Toshitaka Kajino [b,c], Tomoyuki Maruyama [d], Grant J. Mathews [e]

[a] Department of Physics, Soongsil University, Seoul 156-743, Republic of Korea
[b] National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
[c] Department of Astronomy, Graduate School of Science, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan
[d] College of Bioresource Sciences, Nihon University, Fujisawa 252-8510, Japan
[e] Center for Astrophysics, Department of Physics, University of Notre Dame, IN 46556, USA

ARTICLE INFO

Article history:
Received 10 June 2012
Received in revised form 17 September 2012
Accepted 24 September 2012
Available online 4 October 2012

Keywords:
Neutron stars
Magnetic field
Quantum hadrodynamics
Starquakes
Magnetar
Glitches

ABSTRACT

We study the quantum hadrodynamic (QHD) equation of state for neutron stars (with and without including hyperons) in the presence of strong magnetic fields. The calculated adiabatic index for magnetized neutron stars based on the QHD model exhibit rapid changes with density. This may provide some insight into the mechanism of star-quakes and flares in magnetars. We also investigate the strong magnetic field effects on the moments of inertia of neutron stars. The change of the moments of inertia associated with emitted magnetic flares is shown to match well with observed glitches in some magnetars. In our QHD model, the deduced masses and radii of neutron stars without hyperons are consistent with recent observations of high mass neutron stars, while those with hyperons turn out to be less than the recent high mass neutron star.

1. Introduction

Soft γ-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are believed to be evidence for magnetars [1], i.e. neutron stars with surface magnetic fields of 10^{14}–10^{15} G [2]. In the interior of these magnetic neutron stars, the magnetic field strength could be as much as 10^{18} G according to the scalar virial theorem. Such strong magnetic fields may affect the properties of neutron stars such as the relative populations of various particles, the equation of state, and the mass-radius relation. Many studies of dense nuclear matter in the presence of strong magnetic fields have been reported [3–12]. These works have considered the electromagnetic interaction, the Landau quantization of charged particles, and the baryon anomalous magnetic moments (AMMs). However, a detailed analysis of neutron stars with strong magnetic fields is still an area of active research.

Recently, a giant γ-ray flare, SGR 1806-20, has been observed [13]. The total flare energy was estimated to be as much as 2×10^{46} erg. This is $\sim 10^2$ times higher than the two previously observed giant flares [14,15], and is believed to have been released during a reconfiguration of magnetic fields of the neutron star. In Ref. [16], the similarities between SGR events and star-quakes relating to the sudden change of pulsar periods were discussed, and the possibility that SGRs may be powered by star-quakes was suggested. These phenomena might be explained by sudden change in the magnetic pressure.

Although many uncertainties remain regarding star-quakes and the strength of magnetic fields in the interior of neutron stars, it has been suggested [5] that neutron-star matter might be unstable in the presence of strong magnetic fields because of the onset of discrete Landau level energy quantization. This can cause rapid changes in the pressure response to changes in density. This instability could be one source for star-quakes. Thus, one may conjecture the following unifying scenario from star-quakes to pulsar glitches. If a strong magnetic field can cause star-quakes, it may crack the surface of the star. Magnetic field energy may then be released through the cracks. The released magnetic energy and associated reconnection may be observed as a SGR or a giant flare. In addition, the release of the magnetic field energy density may affect the equation of state (EOS) of the neutron star. This, in turn, could give rise to a change of the moment of inertia, and thus, the neutron-star spin period.

In Ref. [5], properties of magnetic stars were studied, but only in the context of a cold free n, p, e Fermi gas. It could not be determined in that work whether the features of interest would persist with a realistic nuclear equation of state. It is useful, therefore, to reconsider the structure and dynamics of magnetic neutron stars

* Corresponding author.
E-mail address: cheoun@ssu.ac.kr (M.-K. Cheoun).

0927-6505/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.astropartphys.2012.09.005

in the context of a realistic nuclear equation of state. Therefore, in this paper we calculate the populations of particles, the instability in the adiabatic index Γ, the EOS, and the moment of inertia for various magnetic field strengths by using the techniques of quantum hadrodynamics (QHD). We then discuss the possibility that star-quakes and SGR flares might be explained by the rapid change of the adiabatic index Γ with density due to the population of Landau levels. We find that, similar to the Fermi gas approximation [5], the magnetic QHD model also shows an instability, i.e. a sudden change of the adiabatic index as the density increases. As in the free nucleon gas this is attributable to the discrete excitation of Landau levels as the density increases, but also to the appearance of hadronic species at high density. These changes in the adiabatic index lead to a sudden change in the pressure response of the star. Therefore, star-quakes and an associated release of magnetic field energy may take place. Moreover, when we assume that magnetic fields as large as $\sim 10^{18}$ G exist inside the star, we find that a release of magnetic field energy could decrease of the moment of inertia leading to an increase in the spin rate of the star.

In Section 2, we briefly introduce our theoretical framework for magnetized dense matter based upon the QHD approach. A method for calculating the possible change in the moment of inertia by the abrupt variations of the adiabatic index is also presented. Discussions of star-quakes and the neutron-star spin are presented along with numerical results in Section 3. A summary and conclusions are given in Section 4.

2. Theory

2.1. Relativistic mean field Lagrangian with strong magnetic fields

The Lagrangian of the QHD model for dense nuclear matter in the presence of a magnetic field can be derived by introducing a vector potential A^μ. The resulting Lagrangian can be written in terms of the baryon octet, leptons, and five meson fields as follows:

$$\begin{aligned}\mathscr{L} = &\sum_b \bar\psi_b\Big[i\gamma_\mu\partial^\mu - q_b\gamma_\mu A^\mu - M_b^*(\sigma,\sigma^*) - g_{\omega b}\gamma_\mu\omega^\mu - g_{\phi b}\gamma_\mu\phi^\mu \\ &- g_{\rho b}\gamma_\mu\vec\tau\cdot\rho^\mu - \frac{1}{2}\kappa_b\sigma_{\mu\nu}F^{\mu\nu}\Big]\psi_b + \sum_l\bar\psi_l\Big[i\gamma_\mu\partial^\mu - q_l\gamma_\mu A^\mu - m_l\Big]\psi_l \\ &+ \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - U(\sigma) + \frac{1}{2}\partial_\mu\sigma^*\partial^\mu\sigma^* - \frac{1}{2}m_{\sigma^*}^2\sigma^{*2} \\ &- \frac{1}{4}W_{\mu\nu}W^{\mu\nu} + \frac{1}{2}m_\omega^2 w_\mu w^\mu - \frac{1}{4}\Phi_{\mu\nu}\Phi^{\mu\nu} + \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu \\ &- \frac{1}{4}R_{i\mu\nu}R_i^{\mu\nu} + \frac{1}{2}m_\rho^2\rho_\mu\rho^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \qquad (1)\end{aligned}$$

where the indices b and l denote the baryon octet and the leptons (e^- and μ^-), respectively. The effective baryon mass, M_b^*, is simply given by $M_b^* = M_b - g_{\sigma b}\sigma - g_{\sigma^* b}\sigma^*$, where M_b is the free mass of a baryon in vacuum and the $g_{\sigma b}$ are associated coupling constants. The σ, ω and ρ meson fields describe the nucleon–nucleon (N–N) and nucleon–hyperon (N–Y) interactions. The Y–Y interaction is mediated by the σ^* and ϕ meson fields. $U(\sigma)$ is the self interaction of the σ field given by $U(\sigma) = \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4$. $W_{\mu\nu}, R_{i\mu\nu}, \Phi_{\mu\nu}$, and $F_{\mu\nu}$ denote the field tensors for the ω, ρ, ϕ and photon fields, respectively.

The anomalous magnetic moments (AMMs) of the baryons interact with the external magnetic field via terms of the form of $\kappa_b\sigma_{\mu\nu}F^{\mu\nu}$ where $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu,\gamma_\nu]$ and κ_b is the strength of the AMM for a baryon, i.e. $\kappa_p = 1.7928\mu_N$ for a proton with the nuclear magneton, μ_N.

In general, the AMMs could depend upon the matter density. Therefore, one can take account of the medium effect through density dependent AMMs which can be evaluated within the quark meson coupling (QMC) model [12]. In this report, however, we did not take account of the effect of density dependent AMMs because the calculation here is performed within the QHD model.

Table 1
Meson-nucleon coupling constants and coefficients of the σ-meson self-interaction terms used in the QHD model, Eq. (1). They are adjusted to reproduce the saturation properties: $\rho_0 = 0.17\text{fm}^{-3}, E_b = 16$A MeV, $a_{sym} = 32.5$ MeV, $m_N^* = 0.78m_N$, and $K = 285.5$ MeV.

$g_{\sigma N}$	$g_{\omega N}$	$g_{\rho N}$	g_2	g_3
8.06	8.19	7.88	12.139	48.414

Main coupling constants used in our model Eq. (1) are tabulated in Table 1. Recent data from heavy ion scattering show that the symmetry energy may have the density dependence [17], which may lead to density dependence in $g_{\rho N}$. But, in our model, $g_{\rho N}$ is assumed as a constant and fitted to reproduce symmetry energy 32.5 MeV at the saturation density. More synthetic approaches for this density dependence and steeper EOS are at progress.

Energy spectra for the baryons and leptons are given by

$$\begin{aligned}E_b^C &= \sqrt{k_z^2 + \left(\sqrt{M_b^{*2} + 2\nu|q_b|B} - s\kappa_b B\right)^2} + g_{\omega b}\omega_0 + g_{\phi b}\phi_0 + g_{\rho b}I_z^b\rho_{30}, \\ E_b^N &= \sqrt{k_z^2 + \left(\sqrt{M_b^{*2} + k_x^2 + k_y^2} - s\kappa_b B\right)^2} + g_{\omega b}\omega_0 + g_{\phi b}\phi_0 + g_{\rho b}I_z^b\rho_{30}, \\ E_l &= \sqrt{k_z^2 + m_l^2 + 2\nu|q_l|B}, \qquad (2)\end{aligned}$$

where E_b^C and E_b^N denote the energies of charged and neutral baryons, respectively. The Landau quantization for charged particles in a magnetic field is denoted as $\nu = n + 1/2 - sgn(q)s/2 = 0, 1, 2\ldots$, where the sign of the electric charge q is denoted as $sgn(q)$ and $s = 1(-1)$ is for spin up (down).

Chemical potentials for the baryons and leptons are given by

$$\mu_b = E_f^b + g_{\omega b}\omega_0 + g_{\phi b}\phi_0 + g_{\rho b}I_z^b\rho_{30}, \qquad (3)$$

$$\mu_l = \sqrt{k_f^2 + m_l^2 + 2\nu|q_l|B}, \qquad (4)$$

where E_f^b is the baryon Fermi energy and k_f is the lepton Fermi momentum. For charged particles, E_f^b is written as

$$E_f^{b^2} = k_f^{b^2} + \left(\sqrt{m_b^{*2} + 2\nu|q_b|B} - s\kappa_b B\right)^2, \qquad (5)$$

where k_f^b is the baryon Fermi momentum and $\nu = 0$ for neutral baryons.

We apply three constraints for calculating the properties of a neutron stars: (1) baryon number conservation; (2) charge neutrality; and (3) chemical equilibrium. The meson field equations are solved along with the chemical potentials for baryons and leptons subject to these three constraints. The total energy density is then given by $\varepsilon_{tot} = \varepsilon_m + \varepsilon_B$, where the energy density for the matter fields is given as

$$\begin{aligned}\varepsilon_m = &\sum_b \varepsilon_b + \sum_l \varepsilon_l + \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_{\sigma^*}^2\sigma^{*2} + \frac{1}{2}m_\omega^2\omega^2 + \frac{1}{2}m_\phi^2\phi^2 \\ &+ \frac{1}{2}m_\rho^2\rho^2 + U(\sigma), \qquad (6)\end{aligned}$$

and the energy density due to the magnetic field is given by $\varepsilon_B = B^2/2$. The total pressure is then

$$P_{tot} = P_m + \frac{1}{2}B^2, \qquad (7)$$

where the pressure due to the matter fields is obtained from $P_m = \sum_i \mu_i \rho_\nu^i - \varepsilon_m$. The relation between the mass and radius for a static and spherical symmetric neutron star is generated from a