

# Neutron stars including the effects of chaotic magnetic fields and anomalous magnetic moments<sup>\*</sup>

Fei Wu(吴飞)<sup>1;1)</sup> Chen Wu(吴琛)<sup>2;2)</sup> Zhong-Zhou Ren(任中洲)<sup>1,3,4;3)</sup>

<sup>1</sup> Physics Department, Nanjing University, Nanjing 210008, China

<sup>2</sup> Shanghai Institute of Applied Physics, Chinese Academy of Science, Shanghai 201800, China

<sup>3</sup> Center of Theoretical Nuclear Physics, National Laboratory of Heavy-Ion Accelerator, Lanzhou 730000, China

<sup>4</sup> Kavli Institute for Theoretical Physics China, Chinese Academy of Sciences, Beijing 100190, China

**Abstract:** The relativistic mean field (RMF) FSUGold model extended to include hyperons is employed to study the properties of neutron stars with strong magnetic fields. The chaotic magnetic field approximation is utilized. The effect of anomalous magnetic moments (AMMs) is also investigated. It is shown that the equation of state (EOS) of neutron star matter is stiffened by the presence of the magnetic field, which increases the maximum mass of a neutron star by around 6%. The AMMs only have a small influence on the EOS of neutron star matter, and increase the maximum mass of a neutron star by  $0.02M_{\text{sun}}$ . Neutral particles are spin polarized due to the presence of the AMMs.

**Keywords:** magnetic field, neutron stars, equation of state

**PACS:** 21.65.Mn, 26.60.Kp, 26.60.-c **DOI:** 10.1088/1674-1137/41/4/045102

## 1 Introduction

The magnetic field is one of the most important constituents of cosmic space and one of the main sources of the dynamics of interacting matter in the universe. Compact stars under strong magnetic fields have drawn much attention. For instance, some authors have evaluated quasinormal modes of the massive scalar field of the Ernst spacetime describing a black hole immersed in a uniform magnetic field [1–3]. Furthermore, there exist very strong magnetic fields in neutron stars. Observational evidence suggests that the magnetic field strength on the surface of soft gamma repeaters and anomalous X-ray pulsars could be as high as  $10^{14} - 10^{15}$  G [4–9]. It exceeds the critical field strength  $B_c^e = 4.414 \times 10^{13}$  G [10], and thus is expected to significantly influence the properties of neutron stars. Fields larger than  $1 \times 10^{18}$  G are expected in the interior of neutron stars due to the scalar virial theorem. The macroscopic properties, such as mass and radius, will depend sensitively on the EOS of strongly magnetized neutron stars. Therefore, it is necessary to study the effect of strong magnetic fields on the properties of neutron stars.

The energy-momentum tensor of a magnetic field is anisotropic. Strictly speaking, the TOV equation [11, 12] is not valid in this situation. To solve this problem, Lopes and Menezes recently proposed a chaotic magnetic field approximation [13], which is able to avoid this issue. It has been used successfully to study the properties of quark stars [13]. Following this line of thought, in our present work, the chaotic magnetic field approximation is extended to investigate the effect of anomalous magnetic moments (AMMs) on the properties of neutron stars. In Ref. [10], the contributions of proton and neutron AMMs to hadronic EOS were calculated for the first time. It was demonstrated that it is possible for the AMMs to have a significant influence on the EOS of neutron star matter. Later, this was generalized to include the contribution from the eight light baryons [14]. Additionally, in most previous works [15–24], a number density-dependent magnetic field is used. An energy density-dependent magnetic field [13] proposed recently has received little attention so far. One of our tasks in this work is to study the influence of the energy density-dependent magnetic field.

Relativistic mean field (RMF) theory has been widely

Received 25 September 2016, Revised 9 November 2016

<sup>\*</sup> Supported by National Natural Science Foundation of China (11535004, 11375086, 11120101005, 11175085, 11235001), 973 National Major State Basic Research and Development of China (2013CB834400), and Science and Technology Development Fund of Macau (068/2011/A)

1) E-mail: howar6hill@yahoo.com

2) E-mail: wuchenoffd@gmail.com

3) E-mail: zren@nju.edu.cn

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used to study the interaction between baryons and meson fields, since it greatly decreases the complexity of the problem, and has achieved much success [25]. Within the framework of the RMF, Todd-Rutel and Piekarewicz recently proposed the FSUGold model [26], which is able to reproduce the properties of nuclear matter successfully [27]. Recently this model has been utilized to study the EOS of neutron star matter [28]. However, the effect of magnetic field has been neglected in previous works that include hyperons. In this paper we will use the FSUGold model extended to include hyperons to investigate the properties of neutron stars. The effects of both the magnetic field and the AMMs will be considered. The chaotic magnetic field approximation and energy density-dependent magnetic field model will be used.

This work is organized as follows. First we introduce the theoretical framework. Next we study the effect of the magnetic field on the EOS, mass-radius relation and particle density of neutron stars. Then the effect of the AMMs on these properties is discussed. Finally, some conclusions are drawn.

## 2 Theoretical framework

To describe the EOS of hadronic matter, we employ the RMF theory, in which baryons interact via the exchange of  $\sigma$ ,  $\omega$  and  $\rho$  mesons. The baryons under consideration include nucleons and hyperons first investigated by Glendenning [29]. The Lagrangian density of the FSUGold model reads [12]

$$\begin{aligned} \mathcal{L} = & \sum_B \bar{\psi}_B [i\gamma^\mu \partial_\mu - q_B \gamma^\mu A_\mu - m_B + g_{\sigma B} \sigma \\ & - g_{\omega B} \gamma^\mu \omega_\mu - g_{\rho B} \gamma^\mu \vec{\tau} \cdot \vec{\rho}^\mu - \frac{1}{2} \mu_N \kappa_B \sigma_{\mu\nu} F^{\mu\nu}] \psi_B \\ & + \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{\kappa}{3!} (g_{\sigma N} \sigma)^3 - \frac{\lambda}{4!} (g_{\sigma N} \sigma)^4 \\ & - \frac{1}{4} \Omega_{\mu\nu} \Omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + \frac{\zeta}{4!} (g_{\omega N}^2 \omega_\mu \omega^\mu)^2 \end{aligned}$$

Table 2. Model parameters of the FSUGold model [12].

$m_\sigma/\text{MeV}$	$m_\omega/\text{MeV}$	$m_\rho/\text{MeV}$	$g_{\sigma N}$	$g_{\omega N}$	$g_{\rho N}$	$\kappa$	$\lambda$	$\zeta$	$A_v$
491.5	783	763	10.59	14.30	11.77	1.42	0.0238	0.06	0.03

To fix the hyperon-meson coupling constants, we take those in the  $SU(6)$  quark model for  $\rho$  and  $\omega$  coupling constants [12] :

$$\begin{aligned} g_{\rho\Lambda} = 0, g_{\rho\Sigma} = 2g_{\rho\Xi} = 2g_{\rho N}, \\ g_{\omega\Lambda} = g_{\omega\Sigma} = 2g_{\omega\Xi} = \frac{2}{3}g_{\omega N}. \end{aligned} \quad (2)$$

The  $\sigma$  couplings are fixed by fitting hyperon potentials. The obtained couplings are  $g_{\sigma\Lambda} = 6.31$ ,  $g_{\sigma\Xi} = 3.27$ , and

$$\begin{aligned} & - \frac{1}{4} G_{\mu\nu}^2 + \frac{1}{2} m_\rho^2 \vec{\rho}^\mu \cdot \vec{\rho}^\mu + \Lambda_v (g_{\rho N}^2 \vec{\rho}^\mu \cdot \vec{\rho}^\mu) (g_{\omega N}^2 \omega_\mu \omega^\mu) \\ & - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \sum_l \bar{\psi}_l [i\gamma^\mu \partial_\mu - m_l - q_l \gamma^\mu A_\mu \\ & - \frac{1}{2} \mu_B \kappa_l \sigma_{\mu\nu} F^{\mu\nu}] \psi_l. \end{aligned} \quad (1)$$

The sum in  $B$  stands for the entire octet set. 1 represents  $e^-$  and  $\mu^-$ . The static properties of these fermions are listed in Table 1. The  $g$ 's are coupling constants that simulate the strong interaction.  $\kappa, \lambda, \zeta$  and  $\Lambda_v$  describe the interaction between mesons in the FSUGold model. We list the parameters of the FSUGold model in Table 2. The  $m$ 's are masses of various particles.  $\kappa_B$  denotes the coupling strength for the baryon AMM, and  $\mu_N$  is the nuclear magneton. Similarly,  $\kappa_l$  denotes the coupling strength for the lepton AMM, and  $\mu_B$  is the Bohr magneton. The coupling of the AMM and electromagnetic field is introduced via  $\sigma_{\mu\nu} = \frac{i}{2} [\sigma_\mu, \sigma_\nu]$ . The mesonic and electromagnetic field tensors take their usual forms:  $\Omega_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu$ ,  $\vec{G}_{\mu\nu} = \partial_\mu \vec{\rho}_\nu - \partial_\nu \vec{\rho}_\mu$ ,  $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ .

Table 1. Mass, charge, and coupling strength for the AMMs of baryons and leptons considered in this paper [14, 30].

species	mass/MeV	charge/e	coupling strength
p	938.3	1	1.79
n	939.6	0	-1.91
$\Lambda^0$	1115.7	0	-0.61
$\Sigma^+$	1189.4	1	1.67
$\Sigma^0$	1192.6	0	1.61
$\Sigma^-$	1197.4	-1	-0.38
$\Xi^0$	1314.8	0	-1.25
$\Xi^0$	1321.3	-1	0.06
$e^-$	0.51	-1	$1.16 \times 10^{-3}$
$\mu^-$	105.6	-1	$1.17 \times 10^{-3}$

$g_{\sigma\Sigma} = 6.36$  [12].

Within the framework of the RMF theory, meson fields are treated as uniform classical fields. Their equations of motion can be obtained by the application of the action principle [12, 25, 31]. The magnetic field is viewed as an external generated field which has no associated field equation. We also impose  $\beta$ -equilibrium and charge neutrality conditions on the neutron star matter [14, 32].

The main effect of the magnetic field is Landau quantization. The energy spectra for neutron baryons, charged baryons, and leptons are given by [14, 16]

$$\begin{aligned}
 E_s^B &= \sqrt{k_z^2 + (\sqrt{m_B^{*2} + k_x^2 + k_y^2} - s\mu_N \kappa_B B)^2} \\
 &\quad + g_{\omega B} \omega + g_{\rho B} \tau_{3B} \rho, \\
 E_{\nu,s}^B &= \sqrt{k_z^2 + (\sqrt{m_B^{*2} + 2\nu|q_B|B} - s\mu_N \kappa_B B)^2} \\
 &\quad + g_{\omega B} \omega + g_{\rho B} \tau_{3B} \rho, \\
 E_{\nu,s}^l &= \sqrt{k_z^2 + (\sqrt{m_l^2 + 2\nu|q_l|B} - s\mu_B \kappa_l B)^2}, \quad (3)
 \end{aligned}$$

where  $\nu = 0, 1, 2, 3 \dots$  enumerates the Landau levels of charged fermions;  $s$  is  $+1$  for spin-up and  $-1$  for spin-down cases.  $m_B^*$  is the effective mass of the baryon under consideration. When  $\kappa_B$  and  $\kappa_l$  are set to zero, the effect of the AMMs is switched off.

The pressure of neutron star matter is obtained from thermodynamic relations at zero temperature [10, 16, 33]

$$P_M = \sum_i \mu_i \rho_i - \epsilon_M, \quad (4)$$

where  $i$  runs over all fermions considered.  $\mu_i$  and  $\rho_i$  are chemical potential and number density, respectively.  $\epsilon_M$  denotes the energy density of neutron star matter.

To obtain the total energy density and pressure, one must add the contribution of the magnetic field. In the current literature, this is usually done as [16–24]

$$\begin{aligned}
 \epsilon &= \epsilon_M + \frac{B^2}{2}, \\
 P &= P_M + \frac{B^2}{2}. \quad (5)
 \end{aligned}$$

However, this seems problematic, since for a magnetic field the energy-momentum tensor is  $\text{diag}(B^2/2, B^2/2, B^2/2, -B^2/2)$  [34], which is anisotropic. In order to obtain the mass-radius relation of a neutron star, the TOV equation is usually used [11, 35, 36]. For the TOV equation to work, the energy-momentum tensor must take the form  $\text{diag}(\epsilon, P, P, P)$ . It demands that the energy-momentum tensor be isotropic.

To solve this issue, a chaotic field approximation [13] has been proposed recently. In this approach, the pressure of magnetic field is  $B^2/6$  instead of  $B^2/2$ . This is consistent with field theory [37], in which  $P = \frac{1}{3} \langle T_i^i \rangle$ .

Since this approach seems more reasonable, we will adopt it in this paper. Hence, the total energy density and pressure is:

$$\begin{aligned}
 \epsilon &= \epsilon_M + \frac{B^2}{2}, \\
 P &= P_M + \frac{B^2}{6}. \quad (6)
 \end{aligned}$$

The magnetic field varies in the interior of a neutron star, but how it varies is still unknown. In the current literature, it is usually assumed to be exponentially density-dependent [15–24]:

$$B = B^{\text{surf}} + B_0 \left[ 1 - \exp \left( -\beta \left( \frac{n}{n_0} \right)^\theta \right) \right], \quad (7)$$

where  $n$  denotes total number density,  $n_0$  is the nuclear saturation density,  $B^{\text{surf}}$  is the magnetic field on the surface of the neutron star, and  $B_0$  is a fixed value of the order of the magnetic field in the center of the neutron star.  $\beta$  and  $\theta$  are free parameters.

Since how the magnetic field varies in the interior of a neutron star is still unknown, we are free to make other assumptions about the variation of magnetic field. It is the energy density rather than the number density that enters the TOV equation, so it is more natural to let the magnetic field couple to the energy density. We will take this approach, using a model proposed recently in [13]:

$$B = B_0 \left( \frac{\epsilon_M}{\epsilon_0} \right)^\gamma + B^{\text{surf}}, \quad (8)$$

where  $\epsilon_M$  is the energy density of neutron star matter.  $B_0$  is a fixed value of magnetic field, approximately the field strength in the core of the neutron star, set to  $3.1 \times 10^{18}$  G in this work.  $\epsilon_0$  is a fixed value taken to be  $5.01 \text{ fm}^{-4}$ .  $B^{\text{surf}}$  is the magnetic field on the surface of the neutron star, taken as  $1 \times 10^{14}$  G.  $\gamma$  is a free parameter that can be any positive number.

The magnetic field will cause spin polarization of charged particles, due to the coupling of magnetic moment and magnetic field. The spin polarization has an influence on the superfluidity of neutron stars. It is defined as [38]

$$S = \frac{\rho_\uparrow - \rho_\downarrow}{\rho}, \quad (9)$$

where  $\rho$  denotes the number density of the particle under consideration,  $\rho_\uparrow$  is the number density of spin-up particles, and  $\rho_\downarrow$  is the number density of spin-down particles.

### 3 Numerical results

As pointed out by previous works, the energy density and pressure of neutron star matter is insensitive to magnetic fields lower than  $1 \times 10^{18}$  G [13, 39, 40]. Following the approach in Ref. [13], we use a fixed value of magnetic field, namely  $3.1 \times 10^{18}$  G, to perform the computation, only taking account of the variation of magnetic field in the calculation of the total energy density and pressure in Eq. (6). This simplification will not change the results considerably.

### 3.1 Effect of magnetic field

First, we study the effect of magnetic field, while ignoring the effect of the AMMs. It is known that the magnetic field can alter the EOS of neutron star matter. In Fig. 1, we plot the EOS without magnetic field and with magnetic field for  $\gamma = 1, 2, 3, 4, 5$ . The EOS of neutron star matter is stiffened by the magnetic field. The smaller  $\gamma$  is, the stiffer the EOS becomes for  $\epsilon < 6.2 \text{ fm}^{-4}$ . This can be understood as follows. The ratio of pressure to energy density due to magnetic field (equal to  $1/3$ ) is larger than that due to matter (less than  $1/7$ ) in the chaotic magnetic field approach. So the stronger the magnetic field is, the stiffer the EOS becomes. For energy density not too large, the magnetic field is stronger for smaller  $\gamma$ .

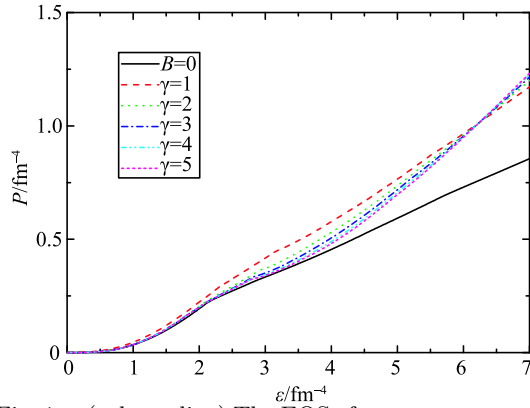


Fig. 1. (color online) The EOS of neutron star matter without the magnetic field and with the magnetic field for different  $\gamma$ .

The stiffening of the EOS will increase the maximum mass of the neutron star. In Fig. 2, the mass-radius relation of the neutron star is displayed. Indeed, the presence of magnetic field produces an increase in the maximum mass. The smaller  $\gamma$  is, the larger the maximum mass and the corresponding radius are. In Table 3, we list the macroscopic properties of maximum mass neutron stars for various configurations. For  $2 \leq \gamma \leq 5$ , the maximum mass is all around  $1.44 M_{\text{sun}}$ , an increase of 6% from the case without magnetic field. For  $2 \leq \gamma \leq 5$ , the maximum mass neutron star has a radius around 10.8 km, smaller than the field-free case (11.4 km).

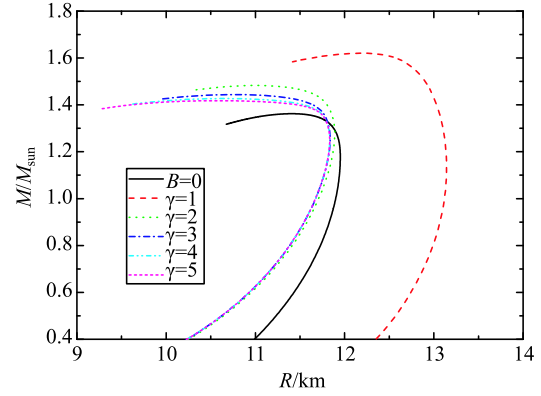


Fig. 2. (color online) Mass-radius relation for neutron stars without the magnetic field and with the magnetic field for different  $\gamma$ .

Table 3. The maximum mass, corresponding radius and central energy density of neutron stars for different magnetic fields with and without the AMMs.

	not including the AMMs			including the AMMs		
	$M/M_{\text{sun}}$	$R/\text{km}$	$\epsilon_c/\text{fm}^{-4}$	$M/M_{\text{sun}}$	$R/\text{km}$	$\epsilon_c/\text{fm}^{-4}$
$B=0$	1.36	11.4	4.86	1.36	11.4	4.86
$\gamma=1$	1.62	12.2	4.76	1.64	12.8	4.69
$\gamma=2$	1.48	11.0	5.72	1.50	11.7	5.41
$\gamma=3$	1.44	10.8	6.10	1.46	11.6	5.61
$\gamma=4$	1.43	10.7	6.33	1.45	11.5	5.62
$\gamma=5$	1.42	10.6	6.52	1.44	11.6	5.52

The magnetic field also alters the relative populations of particles due to Landau quantization. In Fig. 3, we plot the relative populations as a function of baryon density, where  $\rho_0$  is the nuclear saturation density. It can be seen that for  $\rho < 2.5\rho_0$ , the relative populations of proton, electron and muon are altered significantly by the magnetic field, while for larger density  $\rho$ , the change caused by the magnetic field is not as significant as in the low baryon density region. With the increase of baryon density, the Fermi energy of particles becomes

larger, and the ratio of the energy gap between adjacent energy levels of charged particles to their Fermi energy becomes smaller, which leads to a weaker influence of Landau quantization at high density.

The magnetic field not only alters the relative populations of particles, but also alters the fractions of charged particles of the same kind with different spin. In other words, the magnetic field causes charged particles to be spin-polarized. Obviously, in the absence of magnetic field, there will be no spin polarization. In Fig. 4, we

plot the spin polarization as a function of baryon density in the presence of magnetic field. Two species of particles are selected to demonstrate the effect of the magnetic field, namely protons and neutrons, one electrically charged, the other charge neutral. Neutrons are not spin polarized. The magnetic moment decreases the energy of spin-up protons, but increases that of spin-down protons. So the spin polarization of the proton is positive. For  $\rho < 1.4\rho_0$ , the Fermi energy of the proton is so low that all energy levels are occupied by spin-up protons. At higher baryon density, the proton becomes less and less spin-polarized.

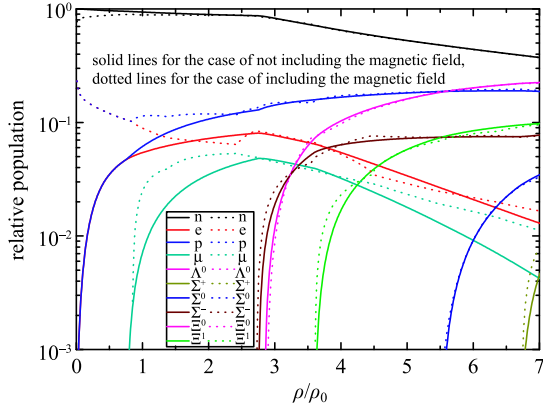


Fig. 3. (color online) Relative population of particles versus baryon density. Solid lines for the case of not including the magnetic field, dotted lines for the case of including the magnetic field.

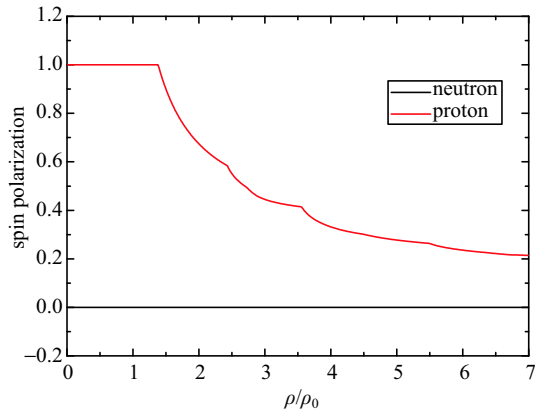


Fig. 4. (color online) Spin polarization of particles versus baryon density in the presence of magnetic field.

### 3.2 Effect of AMMs

Now we are in a position to study the effect of the AMMs. AMMs alter the energy spectra of particles. Particles of the same kind with different spins have different energies. So AMMs influence the spin polarization of

particles. In Fig. 5, spin polarization as a function of baryon density is displayed with and without the inclusion of the AMMs. The most obvious difference between the two cases is that the neutron is spin-polarized in the presence of magnetic field, due to the coupling of the AMM and the magnetic field. Because the AMM of the neutron is negative, its spin polarization is negative. The spin polarization of the proton is increased by its AMM, since its AMM is positive. At lower baryon density, both proton and neutron are more spin-polarized because of their lower Fermi energy.

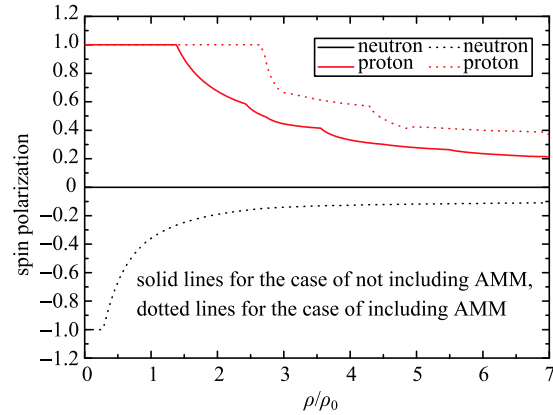


Fig. 5. (color online) Spin polarization of particles versus baryon density with and without AMMs.

The AMMs of particles also influence the EOS of neutron star matter. In Fig. 6 we plot the EOS with and without AMMs for  $\gamma = 3$ . It can be seen that the presence of the AMMs produces a small but not negligible change in the EOS, and the AMMs do not always stiffen or soften the EOS.

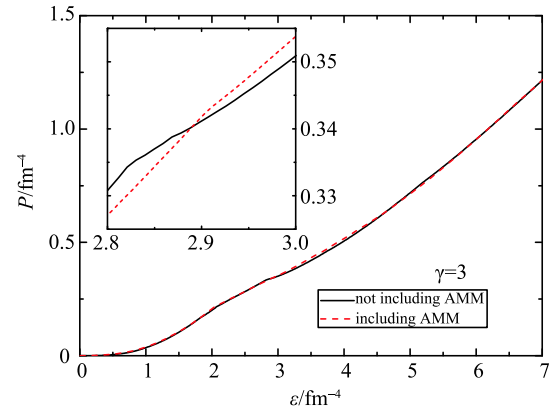


Fig. 6. (color online) The EOS of neutron star matter with and without AMMs.  $\gamma = 3$ .

The small change of EOS caused by the AMMs alters the mass-radius relation of neutron stars. In Fig. 7 the mass-radius relation is plotted with and without the AMMs for  $\gamma = 1, 2, 3, 4, 5$ . It can be seen the curves

are shifted right by the AMMs. In the presence of the AMMs, neutron stars with the same mass will have a larger radius. The macroscopic properties of maximum mass neutron stars with and without the AMMs can be seen from Table 3. For  $1 \leq \gamma \leq 5$ , the maximum mass is increased by  $0.02 M_{\text{sun}}$ , while the corresponding radius is increased by around 0.8 km by the presence of the AMMs. The AMMs also decrease the central density of a maximum mass neutron star.

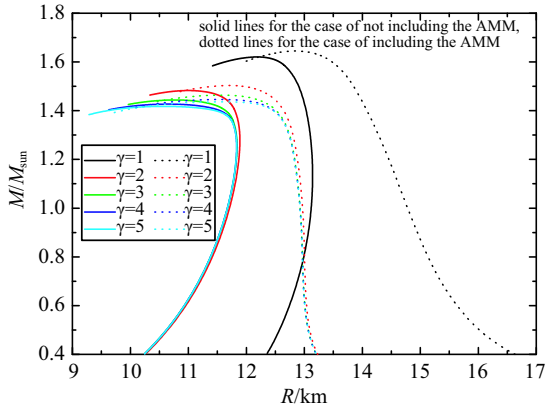


Fig. 7. (color online) Mass-radius relation for neutron stars with and without AMMs.

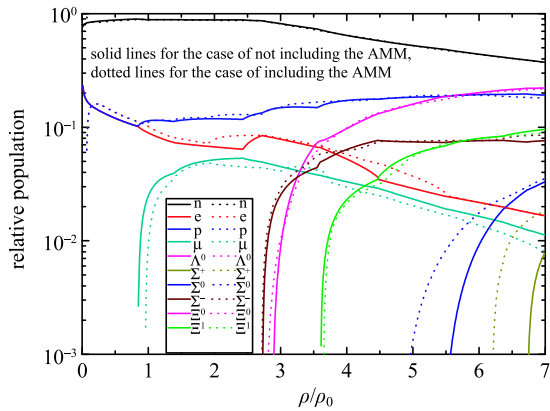


Fig. 8. (color online) Relative population of particles versus baryon density with and without AMMs.

The AMMs also have an influence on the relative populations of particles. We plot the relative populations as a function of baryon density with and without the AMMs in Fig. 8. It can be seen that the AMMs alter the relative populations, but not significantly. The change does not follow a simple pattern.

## 4 Summary and conclusion

In this paper, we use the extended FSUGold model to study the properties of neutron stars with strong magnetic fields. The effect of the AMMs is also taken into account. Our theoretical framework has two major differences from most previous works on the magnetic field. One is that we use the chaotic field approximation, which is able to avoid the anisotropy problem. The other is that we use an energy density-dependent magnetic field model instead of a number density-dependent magnetic field model. We should point out that the maximum observed mass of a neutron star is  $2.01 M_{\text{sun}}$ , a fact that the extended FSUGold model is incapable of explaining. This situation could be remedied by modifying the high density behavior of the model, such as applying the recently proposed  $\sigma$ -cut scheme [41].

It is found that the magnetic field stiffens the EOS. For  $2 \leq \gamma \leq 5$ , it increases the maximum mass of neutron star by about 6%. For baryon density not too large, it alters the relative populations of particles considerably. Charged fermions are spin polarized by the presence of the magnetic field.

The AMMs only have a small influence on the EOS, and increases the maximum mass of neutron star by about  $0.02 M_{\text{sun}}$ . The corresponding radius is increased by about 0.8 km. In addition, neutral fermions are spin polarized by the presence of the AMMs.

*The authors wish to thank Prof. Ren-li Xu and Prof. Xu-guang Huang for useful correspondence.*

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