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# Neutrino Emission and Cooling of Dark-Matter-Admixed Neutron Stars *

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*The GW170817 binary neutron star merger event in 2017 has raised great interest in the theoretical research f neutron stars. The structure and cooling properties of dark-matter-admixed neutron stars are studied here using relativistic mean field theory and cooling theories. The non-self-annihilating dark matter (DM) component is assumed to be ideal fermions, among which the weak interaction is considered. The results show that pulsars J1614-2230, J0348+0432 and EXO 0748-676 may all contain DM with the particle mass of 0.2–0.4 GeV. However, it is found that the effect of DM on neutron star cooling is complicated. Light DM particles favor the fast cooling of neutron stars, and the case is converse for middle massive DM. However, high massive DM particles, around 1.0 GeV, make the low mass (around solar mass) neutron star still undergo direct Urca process of nucleons at the core, which leads the DM-admixed stars cool much more quickly than the normal neutron star, and cannot support the direct Urca process with a mass lower than 1.1 times solar mass. Thus, we may conjecture that if small (around solar mass) and super cold (at least surface temperature 5–10 times lower than that of the usual observed data) pulsars are observed, then the star may contain fermionic DM with weak self-interaction.*

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Through the minimal cosmological standard model, it is believed that dark matter (DM), dark energy and ordinary matter occupy 26.8, 68.3 and 4.9 percent of the total material in the universe, respectively. However, the detailed properties of DM—such as the existence form of DM particles, the particle mass and the interactions among DM—are almost still unknown.[1] However, until now, the quantum of observed pulsars is as high as around 2600 and abundant observed data cumulation can be used by scholars in particle physics and astrophysics. In particular, after advanced LIGO and Fermi/GBM triggered the first binary neutron star (NS) merger, GW170817, on August 17 in 2017, a global observation campaigned covering gamma-ray, x-ray, radio, neutrinos etc.[2–5] Numerous observed data will be enormously helpful for studying NSs, even DM-admixed NSs. So far, several studies have indicated that NSs could capture more DM particles in their formation stage, compared with the uncompacted objects. Consequently, much DM might probably exist in NSs.[6] Furthermore, Brayeur *et al.* have proven that the capture of DM could be highly improved when it happens in binary pulsars.[7] Therefore, we believe that among the numerous ways to study DM, the indirect method of obtaining more information about DM through the global properties of DM-admixed NSs is available and flexible.

The structures of DM-admixed NSs (DMANSs) have recently been studied.[8,9] Ciarcelluti and Sandin pointed out that mirror DM could affect the mass and radius of the NS remarkably.[10] Chen *et al.*[11] have studied isospin-violating bosonic DM. Li *et al.*[12] treated DM particles as fermions, and they found that fermionic DM could soft the equation of state (EOS) and reduce the maximum mass of the NS, while the effect is sensitive to the DM particle mass and the self-interaction within DM. In fact, the interaction between DM and normal matter is usually believed to be the gravitational force, thus the introduction of DM can hardly influence the particle distribution in the NS but can affect the EOS, and change the NS structure consequently.

However, the effect of DM on NS cooling has hardly been investigated. In fact, with the introduction of DM particles, the stellar cooling properties are changed considerably when compared with those of normal NSs. There are three reasons for this. First, for stars with a defined mass, neutrino emissivity is quite different between DMANS and normal NS due to the different stellar structures. Second, the neutrino luminosity consequently varies from DMANS to normal NS. Third, the heat capacity of the DM-admixed NS, which is related to the EOS, becomes different from that of normal NS. Thus, through the above analysis, we believe that the DM particle can affect the neutrino emission and cooling of NSs profoundly. In addition, one may distinguish DM-admixed NS and normal NS through updated astronomical observation data related to age and surface temperature of pulsars.

The properties of normal NS matter can be obtained by the relativistic mean field theory.[13] Here, strong interaction is simulated by the exchange of mesons $\sigma$, $\omega$ and $\rho$, and the details of the Lagrangian density for the system can be seen in Refs. [14-16].

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Then, by solving the Euler–Lagrange equation, meson field equations can be acquired. As a neutral stellar object, NS obeys the charge neutrality, baryon number conservation and chemical equilibrium. Thus, by solving a set of nonlinear equations corresponding to these conservations and field equations, we can obtain the properties of normal NS matter at a fixed density, such as the potentials of mesons, Fermi momentum of the nucleon, chemical potentials of fermions and so on, which are the key quantities to the EOS and cooling properties of the NS. For the normal NS matter, the EOS takes the form

$$\begin{aligned}\varepsilon_0 =& \frac{1}{2}m_\sigma^2\sigma^2 + \frac{b}{3}m_N(g_{\sigma N}\sigma)^3 + \frac{c}{4}(g_{\sigma N}\sigma)^4 \\ &+ \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\rho^2\rho_{03}^2 \\ &+ \sum_N \frac{2J_N+1}{2\pi^2}\int_0^{k_{F_N}} \sqrt{k^2+{m_N^*}^2}k^2dk \\ &+ \sum_l \frac{1}{\pi^2}\int_0^{k_l} \sqrt{k^2+{m_l}^2}k^2dk, \end{aligned} \tag{1}$$

$$\begin{aligned}p_0 =& -\frac{1}{2}m_\sigma^2\sigma^2 - \frac{b}{3}m_N(g_{\sigma N}\sigma)^3 - \frac{c}{4}(g_{\sigma N}\sigma)^4 \\ &+ \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\rho^2\rho_{03}^2 \\ &+ \frac{1}{3}\sum_N \frac{2J_N+1}{2\pi^2}\int_0^{k_{F_N}} \frac{k^4dk}{\sqrt{k^2+{m_N^*}^2}} \\ &+ \frac{1}{3}\sum_l \frac{1}{\pi^2}\int_0^{k_l} \frac{k^4dk}{\sqrt{k^2+{m_l}^2}}, \end{aligned} \tag{2}$$

where $\varepsilon_0$ and $p_0$ represent the energy and pressure density, respectively, and the denotations of other symbols can be seen in Refs. [15,16].

In this work, the non-self-annihilating DM component is assumed to be ideal fermions,[8] and both the energy density and pressure density of DM[17] are written as

$$\varepsilon_{\rm D} = \frac{m_{\rm D}^4}{\pi^2}\int_0^{k_{\rm F}/m_{\rm D}} x^2\sqrt{1+x^2}dx + \left(\frac{1}{3\pi^2}\right)^2\frac{k_{\rm F}^6}{m_{\rm I}^2}, \tag{3}$$

$$\varepsilon_{\rm D} = \frac{m_{\rm D}^4}{3\pi^2}\int_0^{k_{\rm F}/m_{\rm D}} \frac{x^4}{\sqrt{1+x^2}}dx + \left(\frac{1}{3\pi^2}\right)^2\frac{k_{\rm F}^6}{m_{\rm I}^2}, \tag{4}$$

where $m_{\rm D}$ and $k_{\rm F}$ denote the gravitational mass and Fermi momentum of DM particles, respectively, $m_{\rm I}$ represents the self-interaction of DM particles, and there is a weak interaction when the value is around 300 GeV, while there is a strong interaction when the value is around 100 GeV.[12,17] We adopt $m_{\rm I} = 300$ GeV, because only weak self-interaction among DM is considered here. We take the total energy density $\varepsilon$ as $\varepsilon = \varepsilon_0 + \varepsilon_{\rm D}$, and total pressure density $p$. As far as $\varepsilon$ and $p$ are determined, we can obtain the static NS sequences through the TOV equations. The structures of DMANSs and normal NSs can then be gained.

In this work, for the neutrino emission, we focus on the most effective cooling mechanism: direct Urca (dUrca) process of nucleons, which corresponds to the reactions

$$n \to p + l + \overline{\nu_l},\ p + l \to n + \nu_l. \tag{5}$$

The neutrino emissivity[18] can be expressed as

$$\begin{aligned}Q =& \frac{457\pi}{10080}G_{\rm F}^2C^2T^6\Theta(k_l + k_{F_p} - k_{F_n}) \times f_1 g_1[(\varepsilon_{F_n} \\ &+ \varepsilon_{F_p})k_l^2 - (\varepsilon_{F_n} - \varepsilon_{F_p})(k_{F_n}^2 - k_{F_p}^2)] + \varepsilon_{F_n}k_l^2 \\ &- \frac{1}{2}[k_{F_n}^2 - k_{F_p}^2 + k_l^2(\varepsilon_{F_n} + \varepsilon_{F_p})] + 2g_1^2\mu_l m_n^* m_p^* \\ &+ (f_1^2 + g_1^2)[\mu_l(2\varepsilon_{F_n}\varepsilon_{F_p} - m_n^* m_p^*)], \end{aligned} \tag{6}$$

where $G_{\rm F}$ represents the weak-coupling constant, $C = \cos\theta_{\rm c} = 0.973$ is the Cabibbo factor, $C_{\rm V} = 1$ and $C_{\rm A} = 1.26$ denote the vector and axial-vector constants, respectively. Note that the $\Theta$ function actually corresponds to the condition of onset of dUrca process; i.e., when

$$k_{{\rm F}p} + k_{{\rm F}n} \geq k_{{\rm F}e}, \tag{7}$$

the dUrca process for electrons is allowed, which is similar to the situation of muons.

The cooling equation of the NS is written as

$$C_{\rm v}\frac{dT}{dt} = -(L_\nu + L_{\rm r}), \tag{8}$$

from which the NS cooling curves can be obtained. Here, $L_\nu$ and $L_{\rm r}$ denote the neutrino and photon luminosity, respectively, $T$ and $C_{\rm v}$ are the interior temperature and heat capacity of NS, respectively. In fact, $C_{\rm v}$ is related to the NS matter and it is a function of the baryon number density, baryon chemical potential, the EOS and so on. The neutrino luminosity can be obtained by integrating the neutrino emissivity, while the photo luminosity takes the simple form for approximate calculations

$$L_{\rm r} = 7\times10^{36}\left(\frac{R}{10\,{\rm km}}\right)^2 T_{\rm e,7}^4\,{\rm erg\cdot s^{-1}}, \tag{9}$$

where $R$ is the radius of the star, $T_{\rm e,7} = T_{\rm e}/(10^7\,{\rm K})$, and $T_{\rm e}$ is the effect surface temperature in Eq. (9). In general, the relationship between $T_{\rm e}$ and the interior temperature $T$ of the NS is

$$T_{\rm e} = 10^{-2}\alpha T, \tag{10}$$

where $0.1 \leq \alpha \leq 1$. Here, $\alpha = 0.1$ is chosen, assuming that the thermal conductivity of the star is good.

Considering that the latest observations support large mass NS,[19–22] we choose conventional NS matter including neutrons, protons, electrons, and muons for calculations. The GM1 parameter set[23] which leads to a stiff EOS is adopted. Note that DM particles in NS are considered as ideal fermions, among which the interaction is assumed to be the weak interaction.

For different masses of DM particles in NS, ranging from 0.1 GeV to 1.3 GeV, the stellar mass and radius are shown in Fig. 1. It is seen that the maximum

masses of DM-admixed NSs (solid lines) are obviously lower than that of normal NS. With the growth of the mass of DM particles, the maximum mass of NS and the corresponding NS radius decrease. Moreover, in this model we can conjecture that pulsars J1614-2230,[20] J0348+0432[21] and EXO 0748-676[19] may include DM with particle masses of 0.2–0.3 GeV.

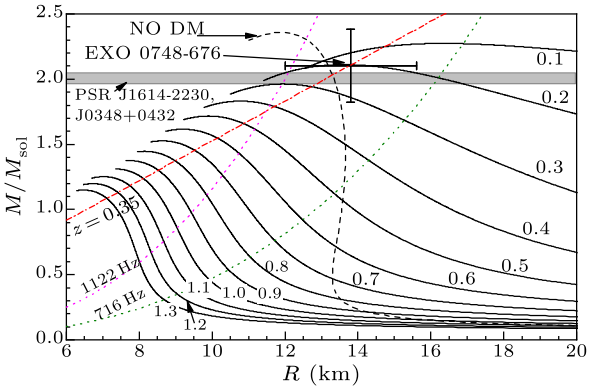



**Fig. 1.** The relationship between DM-admixed (or normal) NS mass and the radius with various masses of DM particles. The dashed line corresponds to normal NS. Pulsars J1614-2230, J0348+0432 and EXO 0748-676 are displayed, as well as the extreme frequencies and red shift value from the observations. Here $M_{\rm sol}$ represents the solar mass.

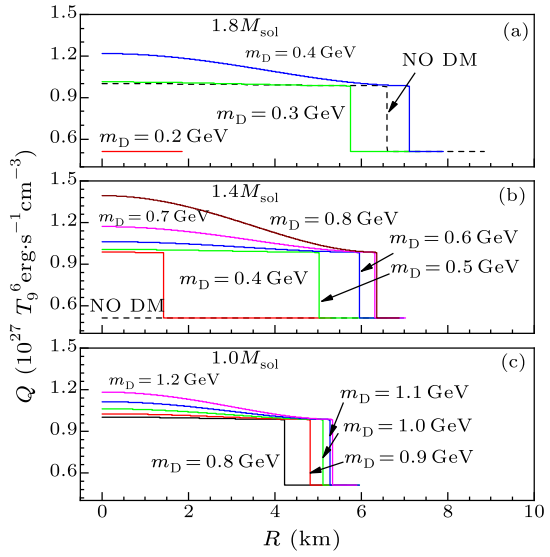



**Fig. 2.** The neutrino emissivity from $1.8M_{\rm sol}$ (a), $1.4M_{\rm sol}$ (b) and $1.0M_{\rm sol}$ (c) NSs. Here, $R$ represents the radial distance in the stellar star, and the curves corresponding to the normal NS are dashed.

The neutrino emissivity from NSs with different NS masses is shown in Fig. 2. With the decrease of the radial distance (increase of density), there is a sudden rise in almost all the curves, which indicates the addition of dUrca process for muons (dUrca$\mu$ process) to the dUrca process for electrons. In fact, from Eq. (6) one can find that the onset of dUrca$\mu$ process enhances the neutrino emissivity violently. For the $1.8M_{\rm sol}$ ($M_{\rm sol}$ represents the solar mass) NS (Fig. 2(a)), it is seen that only the DMANSs with $m_{\rm D}$ = 0.2, 0.3, 0.4 GeV and the normal NS support the occurrence of dUrca process, and the neutrino emissivity at the core of DM-admixed NSs with $m_{\rm D}$ = 0.4 GeV is the highest, whereas $m_{\rm D}$=0.2 GeV is the lowest due to the absence of the dUrca$\mu$ process. However, in the range where the dUrca process is allowed in $1.8M_{\rm sol}$, normal NS is the largest. For the $1.4M_{\rm sol}$ NSs (Fig. 2(b)), normal NS emits the smallest neutrinos because of the low central density, which does not support the condition of the dUrca$\mu$ process. The neutrino emissivity from the core of DMANS becomes higher with the mass of DM particles, a similar situation can also be seen in Fig. 2(c). However, for $1.0M_{\rm sol}$ NSs, the disparity of neutrino emissivity among the DM-admixed NSs with different masses of DM particles is thinner in Fig. 2(c), which indicates that for low-mass DM-admixed NSs, the stellar properties are less sensitive to the mass of DM when compared with those of massive NSs.

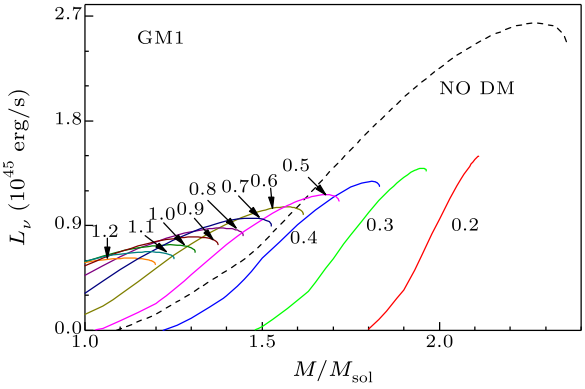



**Fig. 3.** The neutrino luminosity of normal NS and DM-admixed NSs versus the stellar mass. The DM mass is chosen from 0.2 GeV to 1.2 GeV.

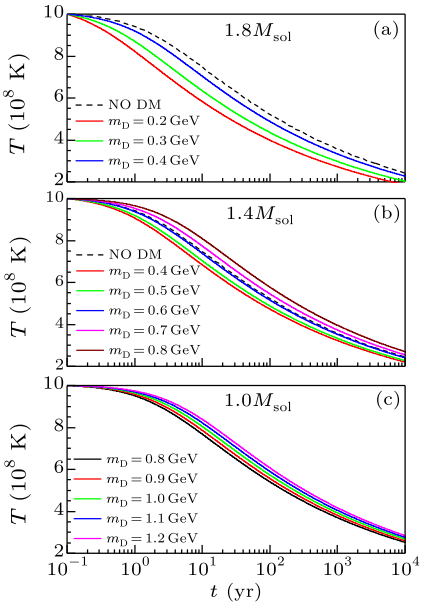



**Fig. 4.** Cooling curves of temperature versus time for NSs with $1.8M_{\rm sol}$ (a), $1.4M_{\rm sol}$ (b) and $1.0M_{\rm sol}$ (c) for various DM particle masses.

The neutrino luminosity of the NS as a function of the stellar mass for various DM masses is shown in Fig. 3. It is seen that the neutrino luminosity of the DMANSs with DM particle masses $m_{\rm D} \leq 0.4$ GeV is

lower than that of normal NS, and for a fixed stellar mass, the neutrino luminosity grows with the DM mass. This is the result of difference between distributions of neutrino emissivity for different NSs (see Fig. 2(a)). When the DM mass becomes as high as 0.7 GeV, the neutrino luminosity of the DM-admixed NSs is much higher than that of normal NS. However, from Fig. 3 we can see that with the increase of DM mass, the neutrino luminosity curve becomes shorter and flatter. This happens because the maximum DM-admixed NS mass becomes smaller with the increase of the DM mass, and the neutrino emission becomes insensitive to the NS mass (see Figs. 1 and 2(c)).

By solving the cooling equation (8), we can obtain the cooling curves of NS; as shown in Fig. 4. Here, the initial time and interior temperature are 0.1 yr and $10^9$ K, respectively. It is seen that for a massive NS, for example, $1.8M_{\rm sol}$ (see Fig. 4(a)), DM makes the star cool faster, and the smaller the DM mass, the faster the cooling. Note that the low luminosity for $m_{\rm D} \leq 0.4$ GeV (see Fig. 3) actually blocks the fast cooling of the star. Thus, from the result in Fig. 4(a), we speculate that the heat capacity of NS favors fast cooling here. However, for the middle mass NS, for example, $1.4M_{\rm sol}$ (see Fig. 4(b)), the DM-admixed NSs with DM mass $m_{\rm D} \leq 0.6$ GeV cool faster than normal NS, while DMANSs with DM mass $m_{\rm D} \geq 0.7$ GeV cool more slowly than normal NS. For $1.0M_{\rm sol}$ small NS (see Fig. 4(c)), the dUrca process cannot be allowed in normal NS, which means that the star will cool very slowly. No enhanced cooling mechanism can occur in normal NS with the mass lower than $1.1M_{\rm sol}$, only a modified Urca process and bremsstrahlung with a neutrino emissivity that is about 7 orders lower than that of dUrca process[24] are allowed. However, with the addition of DM particles, the DMANSs with DM mass $m_{\rm D} \geq 0.8$ GeV still support dUrca process. Thus, for $1.0M_{\rm sol}$ stellar mass, DMANSs with $m_{\rm D} \geq 0.8$ GeV cool faster than normal NS dramatically. For instance, the surface temperature of DMANSs may be 5–10 times lower than that of normal NSs, according to Ref. [24]. However, for the small DMANSs with $1.0M_{\rm sol}$, we can find in Figs. 1–4 that not only the maximum mass of NS but also the neutrino emissivity, neutrino luminosity and the NS cooling rate are less sensitive to the DM particle mass when compared with those for a massive NS. This phenomenon may indicate that there is a DM mass extremity and when closing to it, the effect due to DM can be hardly changed. From the theoretical analysis, we can predict that if small and super cold NSs could be found in the observation, DM particles with the mass 0.8–1.2 GeV may be proven to exist but the accurate DM mass cannot be obtained through this method.

The cooling mechanism of NSs considered here is rough and we mainly calculate the direct Urca process of nucleons. Although other cooling reactions, for example, nucleon pair bremsstrahlung, neutrino pair bremsstrahlung, and direct Urca process of antikaon condensation that can enhance the NS cooling rate are not included, we will carry out these works in the future.

In summary, we have studied the influences of fermionic DM particles on the NS structure, neutrino emission and the cooling of stars. It is found that the properties of DM-admixed NSs are sensitive to the DM mass, especially for massive NSs. Larger DM particles will have a lower maximum NS mass and the neutrino emissivity at the core of NS will be larger. The effect of DM on the NS cooling rate is complicated. Compared with normal NS matter, small DM particles, $0.2 \leq m_{\rm D} \leq 0.4$ GeV, favor the NS cooling and make the massive NS cool faster; middle massive DM particles, $0.6 \leq m_{\rm D} \leq 0.8$ GeV, block the NS cooling and make the NS cool more slowly; high massive DM particles, $0.8 < m_{\rm D} \leq 1.2$ GeV, lead the dUrca process to be allowed in very low mass NSs, around $1.0M_{\rm sol}$, which cannot occur in normal NS. Consequently, if very small and super cold NSs can be found in future astronomical observations, then we may say that massive DM fermions indeed exist in NSs.

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