Signal of quark deconfinement in thermal evolution neutron stars with deconfinement heating

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Abstract

As neutron stars spin-down and contract, the deconfinement phase transition can continue to occur, resulting in energy release(so-called deconfinement heating) in case of the first-order phase transition. The thermal evolution of neutron stars is investigated to combine phase transition and the related energy release self-consistently. We find that the appearance of deconfinement heating during spin-down result in not only the cooling delay but also the increase of surface temperature of stars. For stars characterized by intermediate and weak magnetic field strength, a period of increasing surface temperature could exist. Especially, a sharp jump in surface temperature can be produced as soon as quark matter appears in the core of stars with a weak magnetic field. We think that this may serve as evidence for the existence of deconfinement quark matter. The results show that deconfinement heating facilitates the emergence of such characteristic signature during the thermal evolution process of neutron stars.

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1. Introduction

Fundamental properties of supranuclear matter in the cores of neutron stars, such as the chemical composition and the equation of state, are still poorly known. Simulations of the thermal evolution of neutron stars confronted with soft X-ray, extreme UV, and optical observations of thermal

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As the interior density gradually increases of neutron stars, deconfinement phase transition continuously takes place inducing not only structural changes but also energy release in case of a first-order phase transition. The generation of energy increases the internal energy of the star which is called deconfinement heating (Haensel & Zdunik [1],Yu & Zheng [2],Kang & Zheng [3]). The thermal evolution of neutron stars is connected with their spin-down and the resulting changes in structure and chemical composition (from nucleon matter to deconfined quark matter)have been investigated in our work. We have investigated the thermal evolution of neutron stars with such a deconfinement phase transition(Kang & Zheng [3]). The results show that deconfinement heating delays dramatically the cooling of neutron stars, which have a higher surface temperature compared with traditional cooling for the same age stars.

Many efforts are devoted to explore the observational signal of a deconfinement phase transition which have been suggested in the form of characteristic changes of observables, such as the pulse timing(Glendenning et al.[4],Chubarian et al.[5],Poghosyan et al.[6]), brightness (Dar &DeRújula [7])and surface temperature(Schaab et al.[8], Blaschke et al.[9],Yuan & Zhang [10], Stejner et al.[11]) of the pulsars during their evolution. The surface temperature changes when the quark matter appears in the cores of neutron stars. We explore the deconfinement signature by studying the changes of surface temperature in the thermal evolution process of neutron stars.

In this paper, we reinvestigate the thermal evolution of neutron stars and look for a characteristic change in the surface temperature with deconfinement heating. The released energy can also be estimated as a function of the change rate of the deconfinement baryon number using the parameterized approach. The neutron stars containing quark matter are called hybrid stars. We take Glendenning's hybrid stars model (Glendenning [12]) based on the perturbation theory developed by Hartle[13] to study the rotational evolution structure of stars. The Argonne $V18 + \delta v + UIX^*$ model(APR)(Akmal et al. [14]) of hadronic matter and the MIT bag model of quark matter are used to construct the model of stars, but the medium effect of quark matter has been considered in quasi-particle description(Schertle et al. [15]).

2. Deconfinement phase transition and neutron stars structure

Early works on deconfinement phase transition, the Maxwell construction, show a sharp transition taking place between the two charge-neutral hadron and the quark phases(Baym & Chin [16]). In the 1990s, Glendenning(Glendenning [17], [12]) pointed out that this assumption was too restrictive. More generally, the transition can occur through the formation of a mixed phase of hadron matter and quark matter, with the total charge neutrality being achieved by a positively charged amount of hadronic matter and a negatively charged amount of quark matter. Following Glendenning's model, we use a standard two-phase description of the equation of state(EOS) through which the hadron and quark phases are modelled separately. The resulting EOS of the mixed phase is obtained by imposing Gibbs's conditions for phase equilibrium with the constraint that the baryon number and the electric charge of the system are conserved to the neutron star matter.

The Gibbs condition for chemical and mechanical equilibrium at zero temperature between the two phases reads

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where p_{HP} is the pressure of confined hadron phase and p_{QP} is the pressure of deconfined quark phase.

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$$\epsilon = \frac{E}{V} = \chi\epsilon_{QP} + (1-\chi)\epsilon_{HP} \tag{4}$$

Using the Eqs.(1), (2), (3)and (4), we can obtain the EOS of mixed phase matter. In describing the hadronic part of the neutron star, we adopt the

APR model (Akmal et al. [14]). For the EOS, it is based on the models for the nucleon interaction with the inclusion of a parameterized three-body force and relativistic boost corrections. We use the EOS of an effective mass bag-model for the quark matter part of the neutron star(Schertle et al. [15]).

In Fig.1, we show the model EOS with deconfinement transition, which is the typical scheme of a first-order transition. The phase transition construction in a two-component system leads to a continuous increase in energy per baryon in the mixed phase with increasing density. It is well known that hadron matter is the most stable phase at lower densities, and that quark matter is the most favorite phase at higher densities. Meanwhile, the mixed phase has the lowest energy at intermediate densities. We choose the parameters for quark matter EOS with s quark mass $m_s = 150MeV$, coupling constant $g = 3$ and different bag constant $B = 85MeVfm^{-3}$, $B = 108MeVfm^{-3}$, $B = 136MeVfm^{-3}$ respectively.

With the EOS presented above, we are ready to study the structural evolution of the rotating neutron stars. In this paper, we apply Hartle's approach (Hartle [13]) as in Kang & Zheng [3] to investigate the structure of the stars. By treating a rotating star as a perturbation on a non-rotating star and by expanding the metric of an axially symmetric rotating star in even powers of the angular velocity Ω, we can obtain the structure of the rotating stars.

The resulting gravitational masses of neutron stars for $B = 108MeVfm^{-3}$ are shown in Fig.2, as a function of central baryon density for static stars as well as for stars rotating with the maximum rotation frequency ν_k. The solid almost horizontal connect configurations with the same total baryon number. In order to explore the increase in central density due to spin down, we created sequences of neutron star models. A Model in particular sequence has the same constant baryon number, increasing central density and decreasing angular velocity.

3. Deconfinement heating

There is deconfinement heating production due to spin-down in neutron stars due to the nuclear matter continuously converting into quark matter. The released energy had been estimated as a function the rate of change the deconfinement baryon number using the parameterized approach(Kang & Zheng [3]). Recently we studied the mechanism of energy release in detail(Kang et al. [18]). Through studying a random process of infinitesimal compression for the mixed phase region, we can calculate the energy release per baryon using the following formula

$$\delta\tilde{e} - \delta e = (\frac{\delta\tilde{e}}{\delta\rho_B} - \frac{\delta e}{\delta\rho_B})\delta\rho_B, \tag{5}$$

where $\frac{\delta\tilde{e}}{\delta\rho_B}$ denotes the enthalpy change per baryon .

The deconfinement heating is coupled with the rotation evolution of neutron stars. Combining the energy change with the evolutionary structure of neutron stars, we get the total heat luminosity(Kang et al. [18][19])

$$H_{dec} = \int \frac{de}{dv}\dot{v}(t)\rho_B dV \tag{6}$$

where v is the rotation frequency of the star. The spin-down of stars is due to the magnetic dipole radiation. The rotation frequency is given by

$$\dot{v} = -\frac{16\pi^2}{3Ic^3}\mu^2 v^3 \sin^2\theta \tag{7}$$

where I is the stellar moment of inertia, $\mu = \frac{1}{2}BR^3$ is the magnetic dipole moment, and θ is the inclination angle between the magnetic and rotational axes. We now combine the energy release behavior with spin-down. Our recent work shows that exact calculations agree well with the earlier order of magnitude estimates and supports the previous parameterized approach. Because the change of rotating stars is sufficiently slow, the formula of heat luminosity can be replaced by the simple parameterized form(Kang & Zheng [3]),

$$H_{dec} = \bar{q}\frac{\mathrm{d}N_Q}{\mathrm{d}v}\dot{v}(t) \tag{8}$$

where $\bar{q}$, about 0.1MeV, is the mean value of energy release in the mixed phase and N_Q represents the baryon number of quarks in the interior of the star.

4.Signal of quark deconfinement and thermal evolution of neutron stars

The cooling of neutron stars could take place via two channels - neutrino emission from the entire star and thermal emission of photons through the transport of heat from the internal layers to the surface. Neutrino emission is generated in numerous reactions in the interior of neutron stars, e.g. as reviewed by Page et al.[20]. For the calculation of cooling of the hadronic part of the neutron star, we use the main processes including the nucleon direct Urca (NDU) and the nucleon modified Urca(NMU) and the nucleon bremsstrahlung(NB). For the quark matter, we consider the main process: the quark direct Urca (QDU) processes on unpaired quarks, the quark modified Urca (QMU) and the quark bremsstrahlung(QB). For pure neutron stars, the direct Urca reaction (the most efficient) is allowed only at very high densities because it is impossible to satisfy the conservation of momentum unless the proton fraction exceed the value where both the charge neutrality and the triangle inequality can be observed (Lattimer et al.[21]). However, for neutron stars that contains quark matter, this is not so because charge neutrality does not have to be conserved locally for a mixed phase. Hence the NDU process is active in the mixed phase.

The calculation of the evolution of the thermal energy of neutron stars (heating and cooling) is achieved by coupling their rotating structure and deconfinement phase transition. Fig.3 displays the central density of different masses neutron stars for $B = 108 MeV fm^{-3}$, as a function of their rotational frequency. In Fig.3, the dotted horizontal line indicates the deconfined quark matter produced and dashed horizontal line indicate the NDU processes triggered. In the interior of these stars, the emerging of deconfined quark matter accompanies the gradual energy release leads to rising of surface temperature, and appearance of the NDU process can result in a rapid decrease of the temperature during the spin-down. For $M = 1.5, 1.55, 1.6 M_\odot$ neutron stars, the deconfinement phase transition occurs during the thermal evolution process which may lead to appearance of a characteristic signature. We will now discuss in detail the quark deconfinement signal.

We combine the equation of thermal balance with the rotating structure equations of the stars(Kang & Zheng [3], Hartle [13]) and rewrite the energy equation in the approximation of an isothermal interior(Glen & Sutherland [22])

$$C_V(T_i, v)\frac{dT_i}{dt} = -L_\nu^\infty(T_i, v) - L_\gamma^\infty(T_s, v) \tag{9}$$

$$C_V(T_i, v) = \int_0^{R(v)} c(r, T)(1 - \frac{2M(r)}{r})^{-1/2} 4\pi r^2 dr \tag{10}$$

$$L_\nu^\infty(T_i, v) = \int_0^{R(v)} \varepsilon(r, T)(1 - \frac{2M(r)}{r})^{-1/2} e^{2\Phi} 4\pi r^2 dr \tag{11}$$

Where T_s is the effective surface temperature, $T_i(t) = T(r,t)$ is the redshifted internal temperature; $T(r,t)$ is the local internal temperature of matter, and $\Phi(r)$ is the metric function(describing gravitational redshift)(Yakovlev & Haensel [23]). Furthermore, $L_\nu^\infty(T_i, v)$and $C_V(T_i, v)$ are the total redshifted neutrino luminosity and the total stellar heat capacity, respectively, which are functions of rotation frequency and temperature; $c(r,T)$ is the heat capacity per unit volume. $L_\gamma^\infty = 4\pi R^2(v)\sigma T_s^4(1 - R_g/R)$ is the surface photon luminosity as detected by a distant observer(R_g is the stellar gravitational radius). The effective surface temperature which is detected by a distant observer is $T_s^\infty = T_s\sqrt{1 - R_g/R}$. T_s is obtained from the internal temperature by assuming an envelope model(Gudmundsson et al. [24], Potekhin et al [25]). Using to Eqs.(7)-(11), we can simulate the thermal evolution of neutron stars with deconfinement heating.

In Fig.4 and Fig.5, we present thermal evolution behavior of a $1.6M_\odot$ neutron star for different magnetic fields ($10^9 - 10^{12}$G). Due to the coupling of thermal evolution and spin-down, all curves(with deconfinement heating and without deconfinement heating) show clear magnetic field dependence. During the star's spin down, deconfined quark matter appears in the core of the star at a spin frequency of $v = 1123$Hz, the surface temperature drops rapidly when the NDU process(enhanced cooling) occurs at a spin frequency of $v = 492$Hz. It is evident that the temperature of the curves with deconfinement heating(solid curves) are higher than for the standard cooling scenario without deconfinement(dotted curves). We can observe a competition between cooling and heating processes from the heating curves, where deconfinement heating can produce a characteristic rise of surface temperature and even dominate the history of thermal evolution. Eventually, they reach a thermal equilibrium, where the heat generated is radiated away at the same rate from the star surface. We find the weaker magnetic fields have the larger change of temperature. The low magnetic field (10^9G) produces a sharp jump in surface temperature as soon as the deconfinement quark matter appearing during spin-down. Intermediate magnetic field ($10^{10}, 10^{11}$G) lead to slight changes in the temperature, but high magnetic field form only the temperature plateau at a time.

In Fig.6, we present the cooling behavior of different masses stars for magnetic field B=$10^{12}, 10^{11}$G (left panel) and magnetic field B=$10^9, 10^8$G(right panel) with deconfinement heating. The observational data, taken from tables 1 and 2 in Page et al.[26], have been shown in left panel. Comparing with previous investigation(Kang & Zheng [3]), we find the thermal evolution curves of our present work are more compatible with the observational data(left panel). In our previous work it seemed that, the NDU processes should be triggered easily in the model of relativistic mean field (the critical mass for fast cooling occuring is being low)(Glendenning [12]). In our present study, using the APR EOS, NDU processes can not be triggered easily in stars which lead to the higher temperatures of the evolution curves than in the previous cases. For example, the NDU reactions only appear above 1.56 $M_{\odot}$ in present model. In the cases of weak magnetic field, stars have high temperatures($> 10^5$K) at older ages ($> 10^9$yrs). We thus think that high temperature of some millisecond pulsars with low magnetic fields (Kargaltsev et al [27]), especially for PSR J0437-4715, can be explained using the deconfinement heating model of neutron stars. We can observe that 1.5 $M_{\odot}$ neutron stars follow a similar thermal evolution track as 1.6 $M_{\odot}$, but there is not a period increasing in temperature for $1.7M_{\odot}$. Through comparing Fig.6 with Fig.3, we find the quark matter to appear at the birth of star for $1.7M_{\odot}$. For 1.5 $M_{\odot}$ and 1.6 $M_{\odot}$ stars, quark deconfinement occurs when the central density gradually increases during spin-down, which results in the temperatures of the stars to increase rapidly. This is a characteristic signal as quark matter arises during the rotational spin-down of stars for weak magnetic case.

5. Conclusions and discussions

The chief aim of the present work is to explore the signal of quark matter appearing through theoretical simulation of the thermal evolution curves of neutron stars with deconfinement heating. We have constructed models of rotating neutron stars that follow the mixed phase investigation of Glendenning based on Hartle's perturbative approach. The total thermal luminosities have been obtained using the parameterized approach.

Recently, Stejner et al [11] have investigated the signature of deconfinement with spin-down compression in cooling neutron stars. A period of increasing surface temperature can be produced with the introduction of a pure quark core for strongly superfluid stars of strong and intermediate magnetic field strength and the latent heat of deconfinement reinforces the signature only but is itself relatively less significant. Contrary to their studies, our results show that deconfinement heating can drastically affect the thermal evolution of neutron stars. The rise of surface temperature of cooling stars, as a signature of quark deconfinement, is derived from the deconfinement heating. It is noteworthy that a significant rise of the temperature accompanies the appearance of quark matter at older ages for low magnetic field stars. This may be a evidence for existence of quark matter, if a period of rapid heating is observed for a very old pulsar. Deconfinement heating provides a new way to study the signal of deconfinement.

We found that the deconfined signal appears for neutron stars of mass $1.4M_{\odot} \lesssim M \lesssim 1.64M_{\odot}$. The influence of different EOS of the hadron phase and the model parameters of the quark phase (bag constant B, coupling constant g) on the phase transition densities, rotational structure of neutron stars and corresponding internal structure etc have been studied by many investigators(Schertler et al.[28]; Pan et al.[29]). The deconfinement heating rate and mass range of a deconfinement sinal emerging can be changed with varying of these parameters. In future, we will systematically investigate the effect of these parameters which which will be the subject of our future investigations.

Acknowledgments

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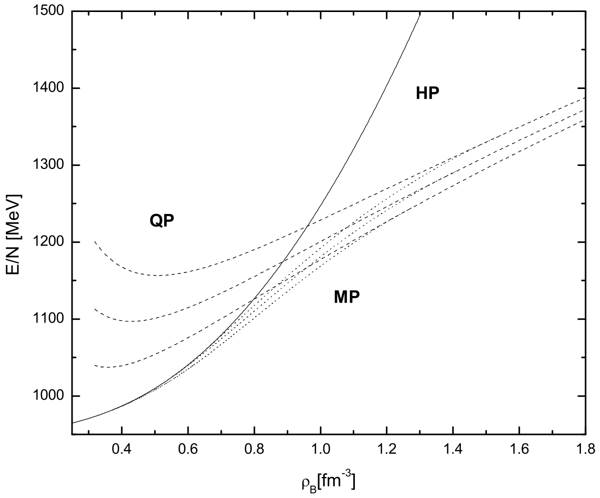

Figure 1: For beta-stable matter, the energy per baryon for the Argonne $V18+\delta\upsilon+UIX^*$ model, and quark effective mass MIT bag model are shown by full and dashed curves(from top to bottom bag constant B=136,108 and 85 $MeVfm^{-3}$ respectively); the dotted lines correspond to neutral mixtures of charged hadron and quark matter

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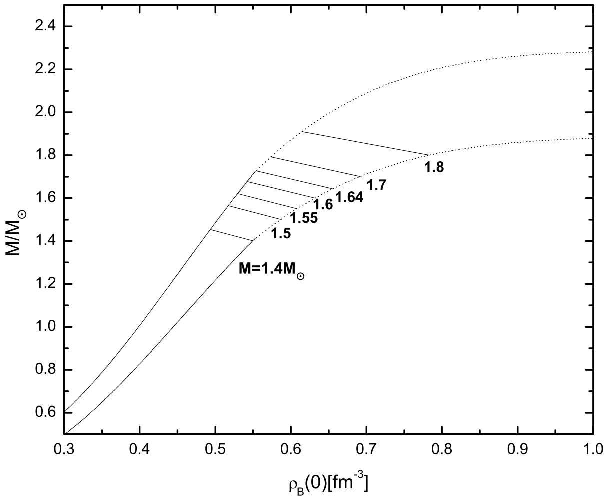

Figure 2: Gravitational mass M in solar masses as a function of the central density for rotating neutron star configurations with a deconfinement phase transition. The lower curve correspond to static configurations. the upper one to those with maximum rotation frequency ν_k. The lines between both extremal cases connect configurations with the same total baryon number. The dotted lines indicate that the quark matter is produced in the core of neutron stars.The bag constant of the quark matter is B=108 $MeV fm^{-3}$

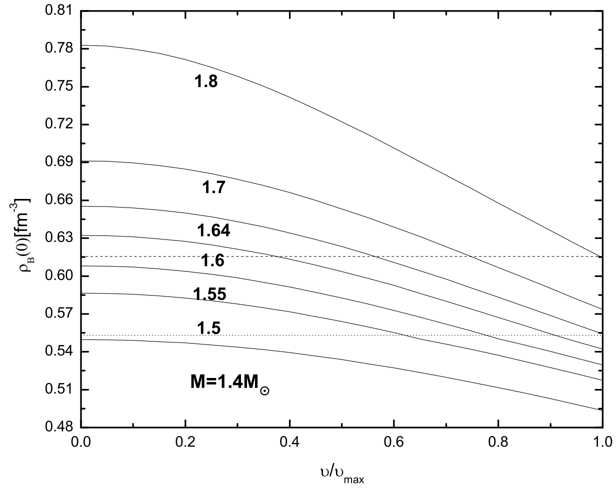

Figure 3: Central density as a function of rotational frequency for rotating neutron stars of different gravitational mass at zero spin. All sequences are with constant total baryon number. Dotted horizontal lines indicate that deconfined quark matter is produced and dashed horizontal lines indicate that the nucleon direct Urca process is triggered.

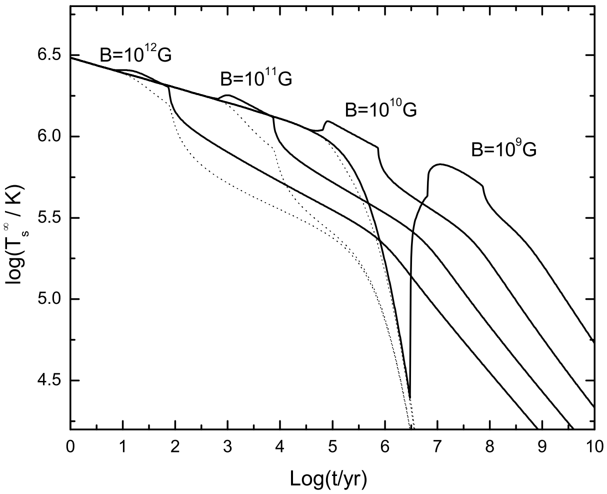

Figure 4: Thermal evolution curves of a 1.6 $M_\odot$ neutron star with deconfinement heating for various magnetic field strengths(solid curves) and the curves without deconfinement heating (dotted curves)

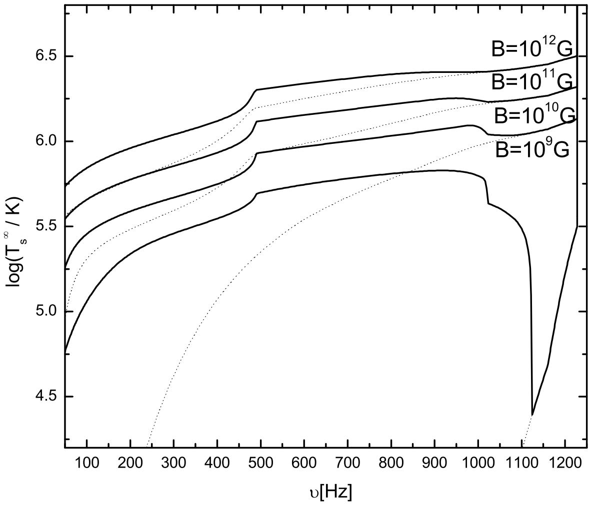

Figure 5: Surface temperature change of a 1.6 $M_\odot$ neutron star with rotational frequency for various magnetic field strengths with deconfinement heating (solid curves) and the curves without deconfinement heating (dotted curves)

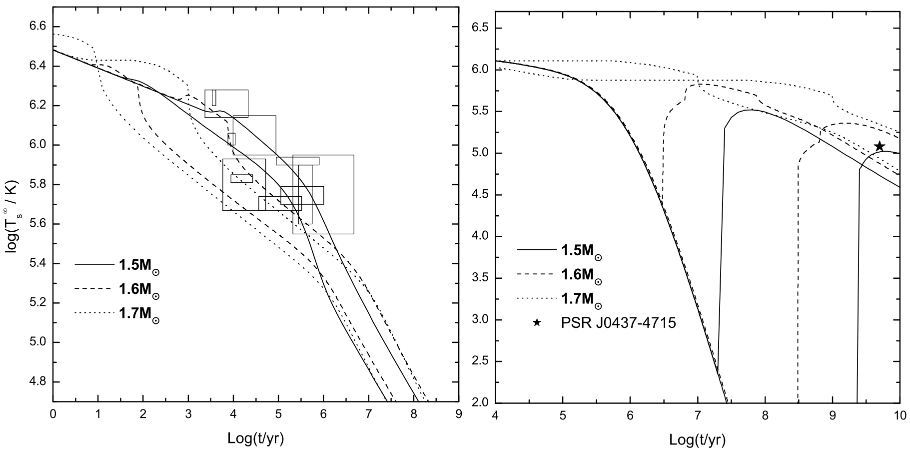

Figure 6: Thermal evolution curves of neutron stars with deconfinement heating for different stars masses and B=10^{12},10^{11}G(left panel) and B=10^{9},10^{8}G(right panel. Rectangles in the left-hand panel indicate observational data on cooling neutron stars with strong magnetic fields.)

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Using the Eqs.(1), (2), (3)and (4), we can obtain the EOS of mixed phase matter. In describing the hadronic part of the neutron star, we adopt the

APR model (Akmal et al. [14]). For the EOS, it is based on the models for the nucleon interaction with the inclusion of a parameterized three-body force and relativistic boost corrections. We use the EOS of an effective mass bag-model for the quark matter part of the neutron star(Schertle et al. [15]).

In Fig.1, we show the model EOS with deconfinement transition, which is the typical scheme of a first-order transition. The phase transition construction in a two-component system leads to a continuous increase in energy per baryon in the mixed phase with increasing density. It is well known that hadron matter is the most stable phase at lower densities, and that quark matter is the most favorite phase at higher densities. Meanwhile, the mixed phase has the lowest energy at intermediate densities. We choose the parameters for quark matter EOS with s quark mass $m_s = 150 MeV$, coupling constant $g = 3$ and different bag constant $B = 85 MeV fm^{-3}$, $B = 108 MeV fm^{-3}$, $B = 136 MeV fm^{-3}$ respectively.

With the EOS presented above, we are ready to study the structural evolution of the rotating neutron stars. In this paper, we apply Hartle's approach (Hartle [13]) as in Kang & Zheng [3] to investigate the structure of the stars. By treating a rotating star as a perturbation on a non-rotating star and by expanding the metric of an axially symmetric rotating star in even powers of the angular velocity Ω, we can obtain the structure of the rotating stars.

The resulting gravitational masses of neutron stars for $B = 108 MeV fm^{-3}$ are shown in Fig.2, as a function of central baryon density for static stars as well as for stars rotating with the maximum rotation frequency ν_k. The solid almost horizontal connect configurations with the same total baryon number. In order to explore the increase in central density due to spin down, we created sequences of neutron star models. A Model in particular sequence has the same constant baryon number, increasing central density and decreasing angular velocity.

3. Deconfinement heating

There is deconfinement heating production due to spin-down in neutron stars due to the nuclear matter continuously converting into quark matter. The released energy had been estimated as a function the rate of change the deconfinement baryon number using the parameterized approach(Kang & Zheng [3]). Recently we studied the mechanism of energy release in detail(Kang et al. [18]). Through studying a random process of infinitesimal compression for the mixed phase region, we can calculate the energy release per baryon using the following formula

$$\delta\tilde{e} - \delta e = (\frac{\delta\tilde{e}}{\delta\rho_B} - \frac{\delta e}{\delta\rho_B})\delta\rho_B, \qquad (5)$$

where $\frac{\delta\tilde{e}}{\delta\rho_B}$ denotes the enthalpy change per baryon .

The deconfinement heating is coupled with the rotation evolution of neutron stars. Combining the energy change with the evolutionary structure of neutron stars, we get the total heat luminosity(Kang et al. [18][19])

$$H_{dec} = \int \frac{de}{dv}\dot{v}(t)\rho_B dV \qquad (6)$$

where v is the rotation frequency of the star. The spin-down of stars is due to the magnetic dipole radiation. The rotation frequency is given by

$$\dot{v} = -\frac{16\pi^2}{3Ic^3}\mu^2 v^3 \sin^2\theta \qquad (7)$$

where I is the stellar moment of inertia, $\mu = \frac{1}{2}BR^3$ is the magnetic dipole moment, and θ is the inclination angle between the magnetic and rotational axes. We now combine the energy release behavior with spin-down. Our recent work shows that exact calculations agree well with the earlier order of magnitude estimates and supports the previous parameterized approach. Because the change of rotating stars is sufficiently slow, the formula of heat luminosity can be replaced by the simple parameterized form(Kang & Zheng [3]),

$$H_{dec} = \bar{q}\frac{\mathrm{d}N_Q}{\mathrm{d}v}\dot{v}(t) \qquad (8)$$

where $\bar{q}$, about 0.1MeV, is the mean value of energy release in the mixed phase and N_Q represents the baryon number of quarks in the interior of the star.

4.Signal of quark deconfinement and thermal evolution of neutron stars

The cooling of neutron stars could take place via two channels - neutrino emission from the entire star and thermal emission of photons through the transport of heat from the internal layers to the surface. Neutrino emission is generated in numerous reactions in the interior of neutron stars, e.g. as reviewed by Page et al.[20]. For the calculation of cooling of the hadronic part of the neutron star, we use the main processes including the nucleon direct Urca (NDU) and the nucleon modified Urca(NMU) and the nucleon bremsstrahlung(NB). For the quark matter, we consider the main process: the quark direct Urca (QDU) processes on unpaired quarks, the quark modified Urca (QMU) and the quark bremsstrahlung(QB). For pure neutron stars, the direct Urca reaction (the most efficient) is allowed only at very high densities because it is impossible to satisfy the conservation of momentum unless the proton fraction exceed the value where both the charge neutrality and the triangle inequality can be observed (Lattimer et al.[21]). However, for neutron stars that contains quark matter, this is not so because charge neutrality does not have to be conserved locally for a mixed phase. Hence the NDU process is active in the mixed phase.

The calculation of the evolution of the thermal energy of neutron stars (heating and cooling) is achieved by coupling their rotating structure and deconfinement phase transition. Fig.3 displays the central density of different masses neutron stars for $B = 108 MeV fm^{-3}$, as a function of their rotational frequency. In Fig.3, the dotted horizontal line indicates the deconfined quark matter produced and dashed horizontal line indicate the NDU processes triggered. In the interior of these stars, the emerging of deconfined quark matter accompanies the gradual energy release leads to rising of surface temperature, and appearance of the NDU process can result in a rapid decrease of the temperature during the spin-down. For $M = 1.5, 1.55, 1.6 M_{\odot}$ neutron stars, the deconfinement phase transition occurs during the thermal evolution process which may lead to appearance of a characteristic signature. We will now discuss in detail the quark deconfinement signal.

We combine the equation of thermal balance with the rotating structure equations of the stars(Kang & Zheng [3], Hartle [13]) and rewrite the energy equation in the approximation of an isothermal interior(Glen & Sutherland [22])

$$C_V(T_i, v)\frac{dT_i}{dt} = -L_{\nu}^{\infty}(T_i, v) - L_{\gamma}^{\infty}(T_s, v) \tag{9}$$

$$C_V(T_i, v) = \int_0^{R(v)} c(r, T)(1 - \frac{2M(r)}{r})^{-1/2} 4\pi r^2 dr \tag{10}$$

$$L_{\nu}^{\infty}(T_i, v) = \int_0^{R(v)} \varepsilon(r, T)(1 - \frac{2M(r)}{r})^{-1/2} e^{2\Phi} 4\pi r^2 dr \tag{11}$$

Where T_s is the effective surface temperature, $T_i(t) = T(r,t)$ is the redshifted internal temperature; $T(r,t)$ is the local internal temperature of matter, and $\Phi(r)$ is the metric function(describing gravitational redshift)(Yakovlev & Haensel [23]). Furthermore, $L_v^\infty(T_i, v)$and $C_V(T_i, v)$ are the total redshifted neutrino luminosity and the total stellar heat capacity, respectively, which are functions of rotation frequency and temperature; $c(r,T)$ is the heat capacity per unit volume. $L_\gamma^\infty = 4\pi R^2(v)\sigma T_s^4(1 - R_g/R)$ is the surface photon luminosity as detected by a distant observer(R_g is the stellar gravitational radius). The effective surface temperature which is detected by a distant observer is $T_s^\infty = T_s\sqrt{1 - R_g/R}$. T_s is obtained from the internal temperature by assuming an envelope model(Gudmundsson et al. [24], Potekhin et al [25]). Using to Eqs.(7)-(11), we can simulate the thermal evolution of neutron stars with deconfinement heating.

In Fig.4 and Fig.5, we present thermal evolution behavior of a $1.6M_\odot$ neutron star for different magnetic fields ($10^9 - 10^{12}$G). Due to the coupling of thermal evolution and spin-down, all curves(with deconfinement heating and without deconfinement heating) show clear magnetic field dependence. During the star's spin down, deconfined quark matter appears in the core of the star at a spin frequency of $v = 1123$Hz, the surface temperature drops rapidly when the NDU process(enhanced cooling) occurs at a spin frequency of $v = 492$Hz. It is evident that the temperature of the curves with deconfinement heating(solid curves) are higher than for the standard cooling scenario without deconfinement(dotted curves). We can observe a competition between cooling and heating processes from the heating curves, where deconfinement heating can produce a characteristic rise of surface temperature and even dominate the history of thermal evolution. Eventually, they reach a thermal equilibrium, where the heat generated is radiated away at the same rate from the star surface. We find the weaker magnetic fields have the larger change of temperature. The low magnetic field (10^9G) produces a sharp jump in surface temperature as soon as the deconfinement quark matter appearing during spin-down. Intermediate magnetic field ($10^{10}, 10^{11}$G) lead to slight changes in the temperature, but high magnetic field form only the temperature plateau at a time.

In Fig.6, we present the cooling behavior of different masses stars for magnetic field B=$10^{12}, 10^{11}$G (left panel) and magnetic field B=$10^9, 10^8$G(right panel) with deconfinement heating. The observational data, taken from tables 1 and 2 in Page et al.[26], have been shown in left panel. Comparing with previous investigation(Kang & Zheng [3]), we find the thermal evolution curves of our present work are more compatible with the observational data(left panel). In our previous work it seemed that, the NDU processes should be triggered easily in the model of relativistic mean field (the critical mass for fast cooling occuring is being low)(Glendenning [12]). In our present study, using the APR EOS, NDU processes can not be triggered easily in stars which lead to the higher temperatures of the evolution curves than in the previous cases. For example, the NDU reactions only appear above 1.56 $M_{\odot}$ in present model. In the cases of weak magnetic field, stars have high temperatures($> 10^5$K) at older ages ($> 10^9$yrs). We thus think that high temperature of some millisecond pulsars with low magnetic fields (Kargaltsev et al [27]), especially for PSR J0437-4715, can be explained using the deconfinement heating model of neutron stars. We can observe that 1.5 $M_{\odot}$ neutron stars follow a similar thermal evolution track as 1.6 $M_{\odot}$, but there is not a period increasing in temperature for 1.7$M_{\odot}$. Through comparing Fig.6 with Fig.3, we find the quark matter to appear at the birth of star for 1.7$M_{\odot}$. For 1.5 $M_{\odot}$ and 1.6 $M_{\odot}$ stars, quark deconfinement occurs when the central density gradually increases during spin-down, which results in the temperatures of the stars to increase rapidly. This is a characteristic signal as quark matter arises during the rotational spin-down of stars for weak magnetic case.

5. Conclusions and discussions

The chief aim of the present work is to explore the signal of quark matter appearing through theoretical simulation of the thermal evolution curves of neutron stars with deconfinement heating. We have constructed models of rotating neutron stars that follow the mixed phase investigation of Glendenning based on Hartle's perturbative approach. The total thermal luminosities have been obtained using the parameterized approach.

Recently, Stejner et al [11] have investigated the signature of deconfinement with spin-down compression in cooling neutron stars. A period of increasing surface temperature can be produced with the introduction of a pure quark core for strongly superfluid stars of strong and intermediate magnetic field strength and the latent heat of deconfinement reinforces the signature only but is itself relatively less significant. Contrary to their studies, our results show that deconfinement heating can drastically affect the thermal evolution of neutron stars. The rise of surface temperature of cooling stars, as a signature of quark deconfinement, is derived from the deconfinement heating. It is noteworthy that a significant rise of the temperature accompanies the appearance of quark matter at older ages for low magnetic field stars. This may be a evidence for existence of quark matter, if a period of rapid heating is observed for a very old pulsar. Deconfinement heating provides a new way to study the signal of deconfinement.

We found that the deconfined signal appears for neutron stars of mass $1.4M_\odot \lesssim M \lesssim 1.64M_\odot$. The influence of different EOS of the hadron phase and the model parameters of the quark phase (bag constant B, coupling constant g) on the phase transition densities, rotational structure of neutron stars and corresponding internal structure etc have been studied by many investigators(Schertler et al.[28]; Pan et al.[29]). The deconfinement heating rate and mass range of a deconfinement sinal emerging can be changed with varying of these parameters. In future, we will systematically investigate the effect of these parameters which which will be the subject of our future investigations.

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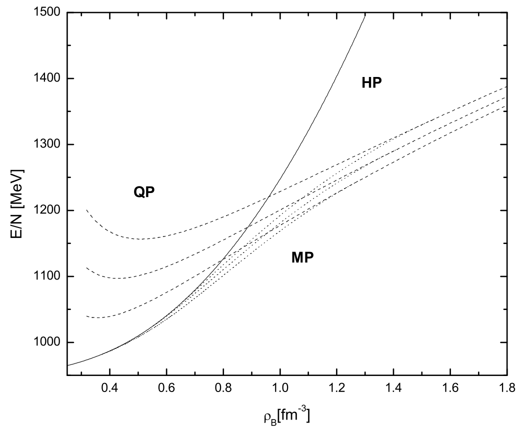

Figure 1: For beta-stable matter, the energy per baryon for the Argonne $V18+\delta v+UIX^*$ model, and quark effective mass MIT bag model are shown by full and dashed curves(from top to bottom bag constant B=136,108 and 85 $MeVfm^{-3}$ respectively); the dotted lines correspond to neutral mixtures of charged hadron and quark matter

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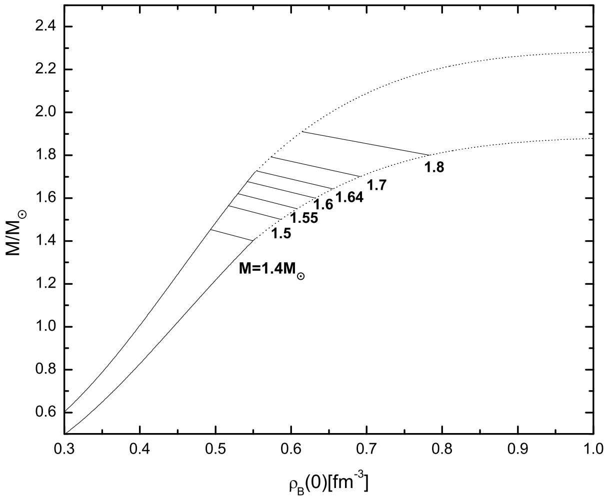

Figure 2: Gravitational mass M in solar masses as a function of the central density for rotating neutron star configurations with a deconfinement phase transition. The lower curve correspond to static configurations. the upper one to those with maximum rotation frequency ν_k. The lines between both extremal cases connect configurations with the same total baryon number. The dotted lines indicate that the quark matter is produced in the core of neutron stars.The bag constant of the quark matter is B=108 $MeV fm^{-3}$

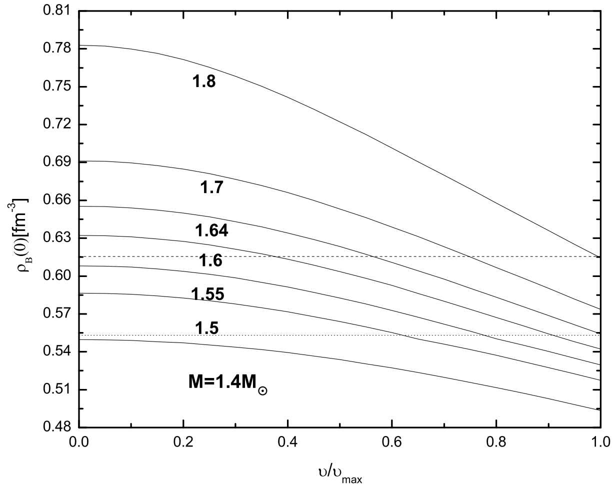

Figure 3: Central density as a function of rotational frequency for rotating neutron stars of different gravitational mass at zero spin. All sequences are with constant total baryon number. Dotted horizontal lines indicate that deconfined quark matter is produced and dashed horizontal lines indicate that the nucleon direct Urca process is triggered.

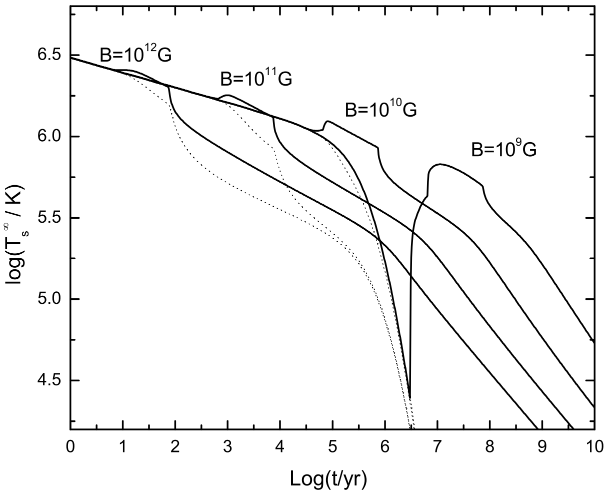

Figure 4: Thermal evolution curves of a 1.6 $M_\odot$ neutron star with deconfinement heating for various magnetic field strengths(solid curves) and the curves without deconfinement heating (dotted curves)

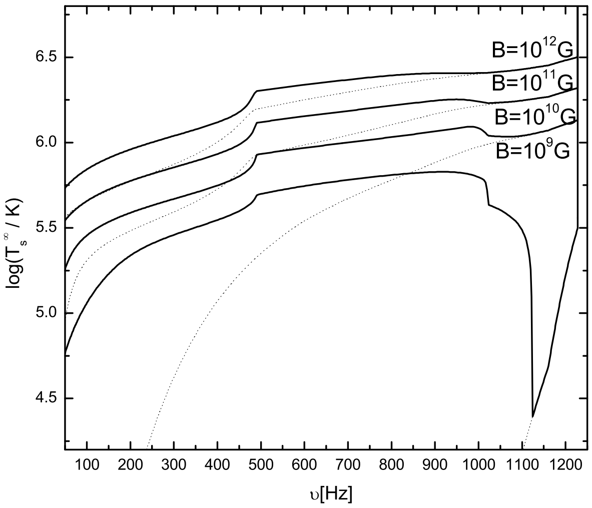

Figure 5: Surface temperature change of a 1.6 $M_\odot$ neutron star with rotational frequency for various magnetic field strengths with deconfinement heating (solid curves) and the curves without deconfinement heating (dotted curves)

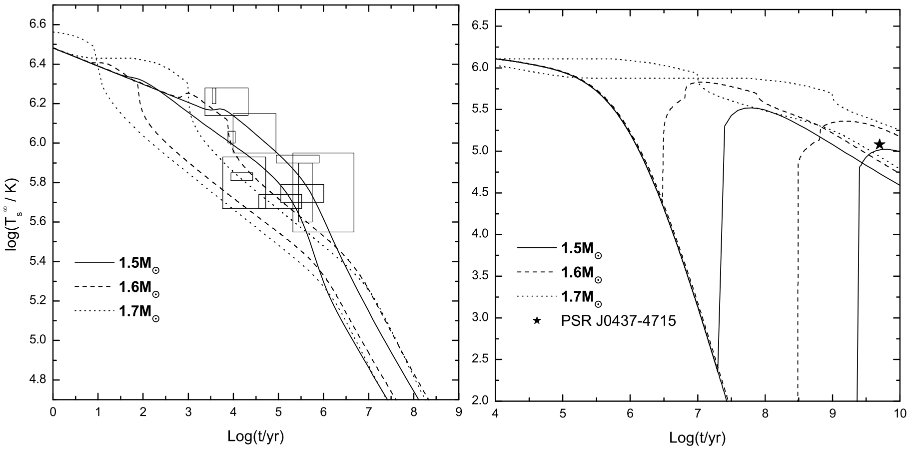

Figure 6: Thermal evolution curves of neutron stars with deconfinement heating for different stars masses and B=10^{12},10^{11}G(left panel) and B=10^{9},10^{8}G(right panel. Rectangles in the left-hand panel indicate observational data on cooling neutron stars with strong magnetic fields.)