〔論　文〕

Neutrino Emissivities from Neutron Stars with Nucleon Superfluidity

Tsuneo NODA*1

Abstract

We study neutrino energy emission rates (emissivities) from the cores of neutron stars. The cores of neutron stars are composed by highly dense nuclear matter which has neutrons, protons, electrons, and some kind of "exotic" particles or states. Neutrino emissivities depend on the state of nuclear matter, and affect the thermal evolutionary scenarios of neutron stars. We summarise the emissivities and the most dominant process at each temperature-density region with various superfluidity models.

Keywords：dense matter, stars: neutron, stars: evolution, pulsars: general, neutrinos, equation of state

1　Introduction

Neutron stars are highly dense stars which are born at the supernovae explosions after the evolution of massive stars. The existence of neutron stars are predicted by Baade & Zwicky[1], and their masses and radii are estimated by Oppenheimer & Volkoff[2]. Finally the first signal of a neutron star was observed by Hewish, Bell et al.[3] Their masses are in the range of 1 to 2 $M_\odot$ ($\odot$ denotes the Sun, 1 $M_\odot = 2.0 \times 10^{30}$ kg), and radii are about 10 km. The mean density of neutron stars reaches to 10^{14} g/cm^3, similar to nuclear density ($\sim 2.7 \times 10^{14}$ g/cm^3). They can be said as "single huge atomic nuclei". Neutron stars are hot at the beginning of their thermal history, however they have no heat sources in the stars. Therefore they emit thermal energy and evolve monotone cooling, if they are isolated stars. Neutron stars emit thermal energy by photons from their surfaces in the range of X-ray, and by neutrinos from their cores. Neutron stars are almost transparent to neutrinos, their mean free path is much larger than radii of neutron stars[4]. Once neutrinos are produced in the star, they escape from the star without any interactions.

Neutron stars are neutron rich composition. A neutron is not a stable particle, causing the beta-decay

$$n \rightarrow p + e^- + \bar{\nu}_e ,$$

creating a proton, an electron and an anti-neutrino with the half-time of 8 minutes. Here, n, p, e^-, ν_e, and $\bar{\nu}_e$ are a neutron, a proton, an electron, an electron neutrino, and an electron anti-neutrino, respectively. Due to the extremely high density, a proton can easily capture a electron

$$p + e^- \rightarrow n + \nu_e ,$$

and form a neutron with emitting a neutrino. They can carry out the thermal energy of the star, and the star cools down with time.

Neutron stars are observed by X-ray observatory satellites. X-ray from outside of the earth, is hardly to detect from the ground of the earth, due to absorption by the atmosphere. The X-ray from the neutron stars is considered as thermal black-body emission at the surface of the stars. The surface temperatures of the stars are in the rage of 10^6 K, and pulled by the core temperatures. The effect of neutrino emission from neutron stars, can be seen by the X-ray observation of the stars. Simulating thermal evolution of the cores of neutron stars can be verified by the X-ray observations.

In this study, we construct the neutrino emissivity calculation module for the thermal evolutionary simulation of whole neutron stars. We report the summary of the emission processes and the rates.

*1 教育創造工学科
平成28年11月30日受理

2 Neutrino Emission Processes from the Core of Neutron Stars

2. 1 Standard Cooling Processes

There are common neutrino emission processes for all neutron stars. Every neutron stars have these processes inside, therefore they are called as "Standard Cooling Process" altogether. The standard cooling contains (mainly) two processes: Modified URCA process for the core, Bremsstrahlung process for the outer core and the crust.

The modified URCA process is the most well-known process of neutron star cooling. In the core of neutron stars, the number of neutrons are much larger than the number of protons and they are well degenerated. The simple beta-decay processes are prohibited, because of breaking the energy momentum conservation. The process has been "modified" from the ordinary beta-decay process by involving another neutron as

$$n + n \rightarrow n + p + e^- + \bar{\nu}_e, \qquad n + p + e^- \rightarrow n + n + \nu_e.$$

The process satisfies the energy-momentum conservation, and it can work in the cores of neutron stars. However, involving one neutron causes the emissivity become smaller than the ordinary beta-decay process. The modified URCA emissivity can be written as

$$\varepsilon_{\rm MU} = 7.4 \times 10^{20} (\rho/\rho_0)^{2/3}\ T_9{}^8 \ {\rm erg\ cm^{-3}\ s^{-1}}.$$

Here, ρ, ρ_0 and T_9 denote the density, nuclear density and temperature normalized by 10^9 K, respectively(5).

The Bremsstrahlung processes (breaking radiation, in English) are the interaction between nucleons, nuclei, and electrons, such as

$$n + n \rightarrow n + n + \nu + \bar{\nu}, \qquad n + p \rightarrow n + p + \nu + \bar{\nu}.$$

Scattering particles changes their orbits, then particles are decelerated and emit radiation. In neutron stars, the radiation creates a neutrino and an anti-neutrino pairs. Both neutrinos in the pair escape from the star without interacting with other particles. This process also take the thermal energy from the star, but weaker than the modified URCA process. The emissivity can be written as

$$\varepsilon_{{\rm BR}-nn} = 1.8 \times 10^{19} (\rho/\rho_0)^{1/3} T_9{}^8 \ {\rm erg\ cm^{-3}\ s^{-1}},$$

$$\varepsilon_{{\rm BR}-np} = 2.0 \times 10^{19} (\rho/\rho_0)^{2/3} T_9{}^8 \ {\rm erg\ cm^{-3}\ s^{-1}}.$$

2. 2 Exotic Cooling Processes

Some kinds of neutrino emission processes appear when the specific condition is satisfied. Pion condensation, Kaon condensation, Quark beta decay, and Hyperon mixing require the density higher than a threshold density of each process, Direct URCA process requires the proton fraction more than a threshold. These processes do not commonly occur in every neutron stars, only in the stars which satisfy the condition. And these emissivities are some order of magnitude higher than the standard cooling processes. In this study, we focus onto the Pion condensation, the Quark beta decay, and the Direct URCA processes.

The Pion condensation process (some calls "Pion URCA") appears in high density region denser than the critical density. Due to high density and pressure, pions appear in the nuclear matter, and condense at the lowest energy state as the Bose-Einstein condensation. These pions decay almost same as beta decay

$$n + \pi^- \rightarrow n + e^- + \bar{\nu}_e, \qquad n + e^- \rightarrow n + \pi^- + \nu_e,$$

and emit large number of neutrinos. The emissivity by the simple model can be written as

$$\varepsilon_\pi \approx 2.0 \times 10^{27}\, \theta^2\ T_9{}^6 \ {\rm erg\ cm^{-3}\ s^{-1}}.$$

Here, θ denotes an angle measuring the degree of pion condensation(6). However, this emissivity is considerably simple, there are much realistic theories and rates investigated. We use the rate calculated by Muto et al.(7), and adopt the

Landau-Midgal parameter $\tilde{g}' = 0.5$[8].

The Quark beta decay process occurs in the quark matter, it requires existence of deconfined quarks. When the confinement of quarks in baryons breaks in the neutron stars, the number difference of u and d quarks is smaller than that of neutrons and protons. The beta decay process

$$d \rightarrow u + e^- + \bar{\nu}_e , \qquad u + e^- \rightarrow d + \nu_e$$

can occur in the matter made by deconfined quarks. They emit large number of neutrinos and anti-neutrinos by the processes above. The emission rate depends on the density, the temperature, the fraction of electron y_e, and the coupling constant α_s. The emissivity can be written as[9]

$$\varepsilon_{\mathrm{Q}} = 8.8 \times 10^{26} \alpha_s (\rho/\rho_0)\, y_e^{1/3}\, T_9^6 \text{ erg cm}^{-3}\text{ s}^{-1}.$$

However, deconfined quarks are considered to be in the Colour Superconducting (CSC) state. Quarks have degrees of freedom of flavour and colour, and they cause some types of pairing to make Cooper pairs[10]. Here we include the effect of the Colour-Flavour Locking (CFL) superconductivity. As discussed in followed section 2.3, CSC have the effect of suppression of emissivity with the critical temperature, similar to the nucleon superfluidity. The critical temperature is combined to the gap energy of super-state, but it is still unknown. We assume the gap $\Delta = 10$ MeV, and demonstrate the emissivity.

The Direct URCA process is differ from other process. It does not require any "exotic" particles, and density condition. The Direct URCA process needs the number fraction of proton reaches to 1/9, where the energy-momentum conservation can satisfy when "normal" neutron beta decay and its inverse reaction can occur. The proton (electron) fraction y_e becomes very small at nuclear density, however it can rise with density. Depending on the equation of state, y_e of core of heavy stars ($\sim 2M_\odot$) can reach to the threshold value[11][12]. Its emissivity can be written as[13]

$$\varepsilon_{\mathrm{DU}} = 4.0 \times 10^{27} (y_e\, \rho/\rho_0)^{1/3}\, T_9^6 \text{ erg cm}^{-3}\text{ s}^{-1}.$$

2.3 Superfluidity Effects

Matter can become superfluid or superconducting state when the temperature becomes significantly low comparing with the characteristic temperature of the matter. Fermi particles around the almost fully degenerate Fermi surface in the phase space, create the Cooper pair, and the pair behaves as a pseudo Bose particle. Bose particles can condensate at lowest energy level.

Interior of neutron star, there are three super-phase conditions. Neutron can condensate in singlet ($^1S_0$) for lower density, and triplet ($^3P_2$) for higher density. Protons also condensate in singlet ($^1S_0$) at medium density region. Protons become superconducting phase because protons are charged particles, and neutrons become superfluid state. The critical temperature of three super-states are density dependent, and the temperature-density region of the transition also depends on models.

When the matter transits to super-state once, it radiate the latent heat by the neutrino emission. This effect is called as "PBF" (Pair Breaking and Formation) process, and it can be the most dominant cooling process[13]. However, this process works just once in the star's lifetime, it make the star cools for a short period and not make large effect afterword.

There is another effect of super-state, once matter becomes to super-state, it reduces thermodynamical effects including other neutrino emission process. The emissivities of other processes are reduced as $\propto \exp(-T_c/T)$ when the matter has been cooled below the critical temperature T_c. In isolated neutron stars, the temperature never rises again, therefore the super-state exists for entire lifetime[14][15].

2.4 Comparison of Emissivities

Here we show 6 neutrino emission processes, and these can work in neutron stars at once. The rates are differed by the orders of magnitude, therefore the most dominant (strongest) process determines the thermal history of neutron stars. However, the effect of super-state is a bit complicated, it cools the star when it transits to super-state, and it

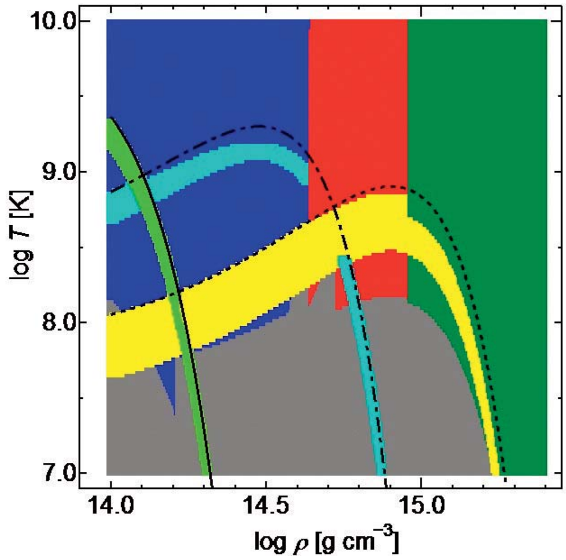

Fig. 1 Showing the most dominant cooling process at each point of density-temperature plane. Blue, Red, Green, Grey, Light Green, Light Blue, and Yellow regions denote Modified URCA, Pion Condensation, Direct URCA, Bremsstrahlung, Neutron $^1S_0$ Superfluidity, Proton $^1S_0$ Superconductivity, and Neutron $^3P_2$ superfluidity, respectively. Solid, dot-dashed and short-dashed lines are the critical temperature of Neutron $^1S_0$, Proton $^1S_0$, and Neutron $^3P_2$, respectively. Quark has never been to the most dominant process with the gap energy $\varDelta$ = 10 MeV.

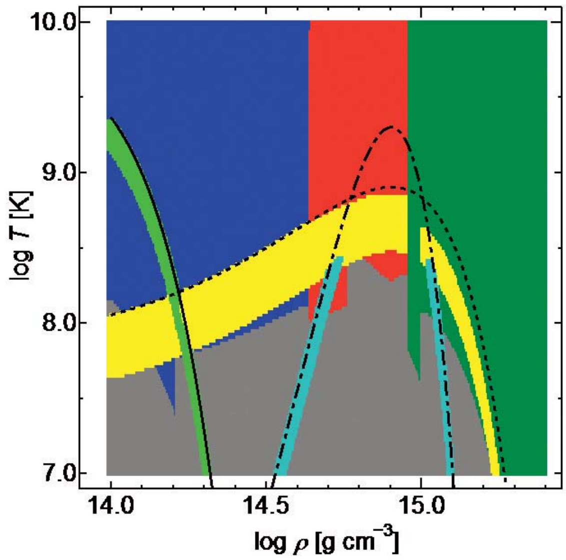

Fig. 2 Same as Fig. 1, but the peak position of the critical temperature of Proton $^1S_0$ moved to higher density.

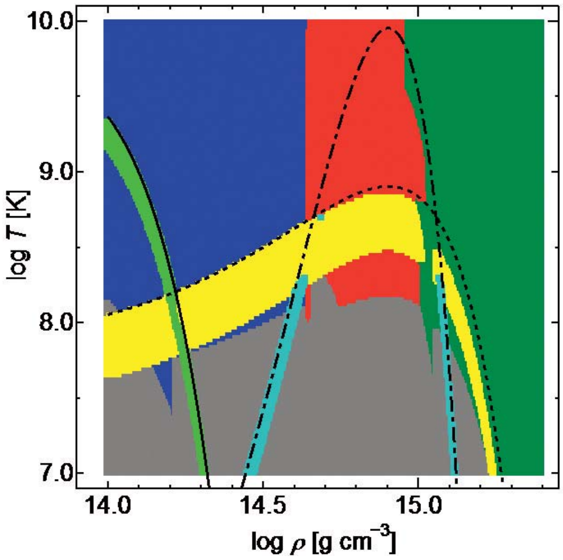

Fig. 3 Same as Fig. 2, but the peak position of the critical temperature of Proton $^1S_0$ moved to higher temperature.

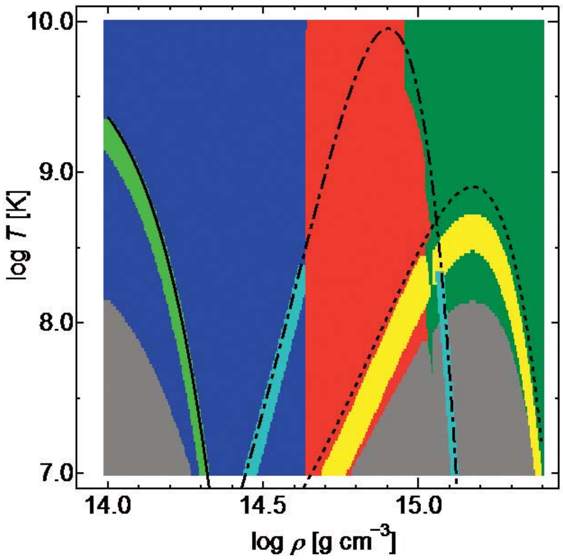

Fig. 4 Same as Fig. 3, but the critical temperature of Neutron $^3P_2$ moved to higher density.

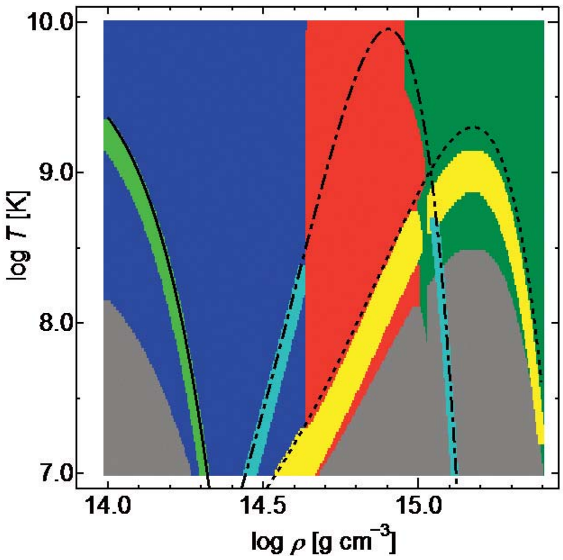

Fig. 5 Same as Fig. 4, but the critical temperature of Neutron $^3P_2$ moved to higher temperature.

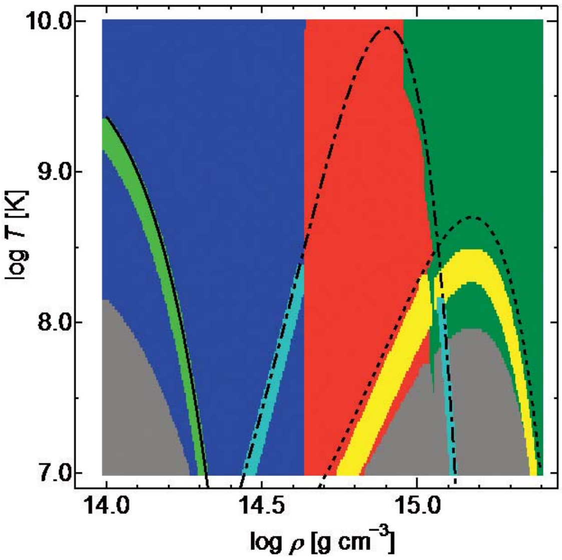

Fig. 6 Same as Fig. 4, but the critical temperature of Neutron $^3P_2$ moved to lower temperature.

reduce the cooling after the transition. The transition occurs when the temperature drops below the critical temperature, and the critical temperature depends on the density and the model.

We demonstrate the most dominant process in the density-temperature plane in Fig. 1-6, with changing the density dependence of the critical temperatures $T_c(\rho)$ for each super-state[16]. The critical temperature $T_c(\rho)$ depends on models of microphysics, for simplify, we modelize it by a Gaussian type function. In Fig. 1-3, we change $T_c(\rho)$ of proton $^1S_0$ state, and we change $T_c(\rho)$ of neutron $^3P_2$ state in Fig. 4-6.

The region of Bremsstrahlung is altered sensitive to the $T_c(\rho)$ of neutron $^3P_2$ state. This means the suppression effect of neutron $^3P_2$ state is the more effective to stronger processes. In this region, the suppression factor is same to all processes, but the emissivities differ in some order of magnitude, the stronger process are affected by the stronger suppression.

3 Summary

In this study, we demonstrate that the most dominant cooling process working in neutron stars. It is sensitive to the critical temperatures of three super-state, especially for the neutron $^3P_2$ state. The emissivities are written in the unit of erg cm^{-3} s^{-1}, showing that the dominant process at each density-temperature region, and not showing the actual cooling rate of the whole stars. To examine which cooling process determines the cooling history of neutron stars, we need to simulate whole stars by the thermal evolutionary code.

We do not include other exotic processes such as Kaon condensation, Hyperons or other paring of Quarks. Especially, Hyperon mixing are considered that they appear at sufficient density, having large emissivities. There are some results of nuclear emulsion experiments, showing that the Λ hyperon cannot make the Cooper pair, due to the repulsive interaction[17]. And the Ξ hyperons would make the pair[18]. We will include them to our further calculation[19][20]. We will simulate the thermal evolution of neutron stars, including the results of this study, and determine the parameter-region of each critical temperatures of super-states. Simulating neutron stars can make constraints on the microphysics, such as nuclear physics theory and superfluid/superconducting theory.

Acknowledgements

I would like to thank Prof Masa-aki Hashimoto, Mr Yasuhide Matsuo, and Dr Ken'ichiro Nakazato for helpful discussions about the nuclear matter. Also, I wish to thank Prof Fumihiko Nakamura for useful advices about superfluid/superconductivity.

References

(1) W. Baade & F. Zwicky, *Phys. Rev.* **45**, 138 (1934).
(2) J. R. Oppenheimer & G. M. Volkoff, *Phys. Rev.* **55**, 374 (1939).
(3) A. Hewish, S. J. Bell, J. D. H. Pilkington, P. F. Scott & R. A. Collins, *Nature*, **217**, 709 (1968).
(4) S. L. Shapiro & S. A. Teukolsky, "Black Holes, White Dwarfs, and Neutron Stars", Wiley Interscience, 1983.
(5) B. L. Friman & O. V. Maxwell, *Astrophys. J.* **232**, 541 (1979).
(6) O. Maxwell, G. E. Brown, D. K. Campbell, R. F. Dashen & J. T. Manassah, *Astrophys. J.* **216**, 77 (1977).
(7) T. Muto & T. Tatsumi, Prog. *Theor. Phys.* **78**, 1405 (1987).
(8) H. Umeda, K. Nomoto, S. Tsuruta, T. Muto & T. Tatsumi, *Astrophys. J.* **431**, 309 (1994).
(9) N. Iwamoto, *Phys. Rev. Lett.* **44**, 1637 (1980).
(10) S. B. Rüster, V. Werth, M. Buballa, I. A. Shovkovy & D. H. Rischke, *Phys. Rev. D*, **72**, 034004 (2005).
(11) P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts & J. W. T. Hessels, *Nature*, **467**, 1081 (2010).
(12) J. Antroniadis et al. *Science*, **340**, 448 (2013).
(13) J. M. Lattimer, C. J. Pethick, M. Prakash & P. Haensel, *Phys. Rev. Lett.* **66**, 2701 (1991).
(14) S. Tsuruta, *Phys. Rep.* **292**, 1 (1998).
(15) D. G. Yakovlev, A. D. Kaminker, O. Y. Gnedin & P. Haensel, *Phys. Rep.* **354**, 1 (2001).
(16) T. Takatsuka & R. Tamagaki, *Prog. Theor. Phys.* **67**, 1649 (1982).
(17) H. Takahashi et al. *Phys. Rev. Lett.* **87**, 212502 (2001).
(18) N. Nakazawa et al. *Prog. Theor. Exp.* Phys. **2015**, 033D02 (2015).
(19) T. Noda, M. Hashimoto, N. Yasutake, T. Maruyama, T. Tatsumi & M. Y. Fujimoto, *Astrophys. J.* **765**, 1 (2013).
(20) M. Hashimoto, K. Hayashida, Y. Matsuo, T. Noda & M. Y. Fujimoto, Submitted to *Phys. Rev. D* (2016).