Signal of quark deconfinement and thermal evolution of hybrid stars

Miao Kang  
The College of Physics and Electronics  
Henan University  
Kaifeng, 475004  
P. R. China  
Email: kangmiao07@gmail.com

1 Introduction

It is well known that neutron stars spin down due to magnetic dipole radiation. The deconfinement phase transition of hadron matter to quark matter is expected to occur in the dense cores of the stars during spin-down [1][2]. The 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 stars which is called deconfinement heating [3][4][5]. The temperature of the stars arise when the deconfinement heating appears in the cores. We explore the deconfinement signature by studying the changes of surface temperature in the thermal evolution process of neutron stars.

2 Method and Result

Following Glendenning's hybrid stars model [2][6], 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 [7]. The Argonne V18 + δv + UIX*(APR) model [8] of hadronic matter and the MIT bag model of quark matter [9] are used to construct the model of 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 [10] as in Kang & Zheng [11].

The deconfinement heating is coupled with rotating evolution of the stars. Combining the energy change with the evolutionary structure of hybrid stars, we get the total heat luminosity [5][12]

\[ H_{\text{dec}} = \int \frac{de}{dv} \dot{v}(t) \rho_B dV \]  

(1)
the rotation frequency is given by
\[
\dot{v} = -\frac{16\pi^2}{3Ic^3} v^3 \sin^2 \theta.
\] (2)

The traditional standard cooling model often based on the Tolman-Oppenheimer-Volkoff equation of hydrostatic equilibrium [13][14] do not consider rotational evolution of the stars. We combine the equation of thermal balance with the rotating structure equations of the stars and rewrite the energy equation in the approximation of an isothermal interior (Kang & Zheng [11])

\[
C_V(T_i, v) \frac{dT_i}{dt} = -L_\nu^\infty (T_i, v) - L_\gamma^\infty (T_s, v)
\] (3)

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

\[
L_\nu^\infty (T_i, v) = \int_0^{R(v)} \varepsilon(r, T)(1 - \frac{2M(r)}{r})^{-1/2} e^{2\Phi} 4\pi r^2 dr.
\] (5)

Where \(C_V(T_i, v)\) is the total stellar heat capacity, \(L_\nu^\infty (T_i, v)\) and \(L_\gamma^\infty = 4\pi R^2(v)\sigma T_s^4(1 - R_g/R)\) are the total redshifted neutrino luminosity and the surface photon luminosity, respectively, which are functions of rotation frequency and temperature. Neutrino emission is generated in numerous reactions in the interior of neutron stars, e.g. as reviewed by Page et al. [13]. The most powerful neutrino emission is provided by the direct Urca processes (the nucleon direct Urca process and the quark direct Urca process). Using to Eqs.(2)-(5), we can simulate the thermal evolution of neutron stars with deconfinement heating.

In Fig 1, we present thermal evolution behavior of a 1.6\(M_\odot\) 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. 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 field have the larger change of temperature. The low magnetic field (10\(^9\)G) 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 2, 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. [15], have been shown in left panel. Comparing with previous investigation [5], we find the thermal evolution curves of our present work are more compatible with the observational data (left panel). 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. 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 [16], especially for PSR J0437-4715, can be explained using the deconfinement heating model of hybrid stars. We can observe that 1.5 $M_\odot$ stars follow a similar thermal evolution track as 1.6 $M_\odot$, but there is not a period increasing in temperature for 1.7$M_\odot$. The reason for this is that the quark matter to appear at the birth of the stars 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.
Figure 2: 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.)

3 Conclusions

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.

4 Acknowledgements

This work is supported by NFSC under Grant Nos.10747126 and 10773004.

References

[1] G. Baym, S. A.Chin, Phys.Lett.B, 62,241(1976)
[2] N. K. Glendenning, Phys. Rev. D, 46, 1274(1992)

[3] P. Haensel, J. Zdunik, In: J. Madsen, P. Haensel (eds.) Strange Quark Matter in Physics and Astrophysics. (Nucl. Phys. B [Proc. Suppl.] 24), 139(1991)

[4] Y. W. Yu, X. P. Zheng, A&A, 445, 627(2006)

[5] M. Kang, X. P. Zheng, MNRAS, 375, 1503(2007)

[6] N. K. Glendenning, Compact Stars (Springer-verlag), (1997)

[7] K. Schertler, C. Greiner, J. Schaffner-Bielich, & M. H. Thoma, Nucl. Phys. A, 677, 463(2000).

[8] A. Akmal, V. R. Pandharipande, & D. G. Ravenhall, Phys. Rev. C, 58, 1804(1998)

[9] K. Schertler, C. Greiner, & M. H. Thoma, Nucl. Phys. A, 616, 659(1997)

[10] J. B. Hartle, ApJ, 150, 1005(1967)

[11] M. Kang, X. D. Wang, & N. N. Pan, RAA, 9, 1351(2009)

[12] M. Kang, X. P. Zheng, & N. N. Pan, astro-ph/0708.0900(2007)

[13] D. Page, U. Geppert, & F. Weber, Nucl. Phys. A, 777, 497(2005)

[14] D. G. Yakovlev, C. J. Pethick, Ann. Rev. Astron. Astrophys, 42, 169(2004)

[15] D. Page, J. M. Lattimer, M. Prakash, & A. W. Steiner, ApJS, 155, 623(2004)

[16] O. Kargaltsev, G. G. Pavlov, & R. Romani, APJ, 602, 327(2004)