Deconfinement Phase Transition Heating and Thermal Evolution of Neutron Stars

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ABSTRACT

The deconfinement phase transition will lead to the release of latent heat during spins down of neutron stars if the transition is the first-order one. We have investigated the thermal evolution of neutron stars undergoing such deconfinement phase transition. The results show that neutron stars may be heated to higher temperature. This feature could be particularly interesting for high temperature of low-magnetic field millisecond pulsar at late stage.

Probing the equation of state (EOS) of neutron star matter is a urgent task in studying compact stars. Both the determination of mass-radius relation$^{[1][2]}$ and spin evolution of compact stars$^{[3][4][5][6][7][8]}$ are usual methods. Neutron stars (NSs) cooling is another important tool for the study of dense matter$^{[9][10]}$. By comparing cooling models with thermal emission data from observations, we can gain insight into the EOS of dense matter inside NSs. Heating source inside the stars is an important factor effect in the cooling of NSs.

It is known that a NS will spin down due to braking (e.g. electric-magnetic radiation or gravitational wave radiation). The deconfinement phase transition from hadronic matter to quark matter can continuously occur in NSs during the spins down. Many investigations were interesting in the phase transition which is of the first-order type$^{[11][12]}$. Such deconfinement processes induce continuous release of latent heat. The generation of the energy increases internal energy of the star. It will be called deconfinement heating (DH). DH have been investigated in strange stars, where neutron drops at the bottom of a crust drip on to the quark matter surface to be instantaneously dissolved into quark matter$^{[13][14]}$.

Most of the approaches to deconfined matter in NSs use a standard two-phase description of EOS where the hadron phase and the quark phase are modelled separately and resulting EOS of the mixed phase is obtained by imposing Gibbs conditions for phase equilibrium with the constraint that baryon number as well as electric charge of the system are conserved$^{[15]}$. Assumed the deconfinement phase transition is a first order phase transition, the deconfinement processes should produce latent heat.

Combining with the equation of rotating structure based on Hartle’s perturbation approach$^{[16]}$, we get the total latent heat release unit time for a star in ref$^{[17]}$

\[ H_{dec}(t) = \int \frac{d\nu}{d\nu'} \dot{\nu}(t) \rho_B dV. \] (1)
We can approximate equation (1) using an expression with a parameter $q_n$ \[ H_{\text{dec}}(t) = q_n \frac{dN_q}{d\nu} \dot{\nu}(t) \] (2)

here $q_n$ is the average value of release energy per nucleon transforming into quarks, $N_q$ is deconfinement baryon number, \( \dot{\nu} \) is induced by magnetic dipole radiation. In a strange star with nuclear matter crust, the similar expression has been obtained. However, $q_n$ in our model is $10^{-2}$ times smaller than that of the strange star model (17) (19).

The cooling is realized via two channels - by neutrino emission from the entire star body and by transport of heat from the internal layers to the surface resulting in the thermal emission of photons. Neutrino emission is generated in numerous reactions in the interiors of neutron stars, as reviewed, by Page et al. (9). In this paper, we consider the most powerful neutrino emission including nucleon direct Urca (NDU) processes and quark direct Urca (QDU) processes for the matter of NSs. Nucleon superfluidity and quark superconductivity are not included in the model.

According to the thermal evolution equation (9), we get the thermal evolution curves with DH shown in Fig.1 which shows the cooling behavior of a 1.5 $M_\odot$ NS for different magnetic fields ($10^8$ – $10^{12}$ G), where $q_n$ is taken to be 0.1 MeV. It is evident that the DH increase the surface temperature dramatically. This is extremely different from fast cooling scenario (solid curve). The strong field strength induces a rapid spin-down at the beginning while the low field strength leads to only obvious spin-down at the older ages. In the cases of weak field, stars could maintain high temperatures even at older ages ($> 10^7$ yrs). The temperature is nearly identified with the values observed from millisecond pulsars, especially for PSR J0437-4715 (20).

We find DH's significant effects on the thermal evolution and the effects is much more important than the past present heating mechanisms (21)(22)(23)(24). We can find the remarkable change of temperature in strange stars nuclei where DH leads to too hot millisecond pulsars (14)(25). In future, we expect more observational examples in investigating effects of DH mechanism on the NSs thermal evolution. Another problem which remains to be investigated is the unified description of middle-age and old pulsars. The NSs containing MP matter model may be no bad selection when our combining DH, superfluidity effects in nuclear matter together.

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Fig. 1.— Cooling curves of 1.5 $M_\odot$ neutron star with DH for various magnetic fields and the curves without DH (solid curve).