COOLING DELAY FOR PROTOQUARK STARS DUE TO NEUTRINO TRAPPING

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The influence of neutrino trapping (NT) on the early cooling evolution of hot protoquark stars (PQS) with initial temperatures in the range $T \sim 40$ MeV is studied. Within a simplified model for the neutrino transport it is shown that the time for reaching neutrino opacity temperature of $T_{\text{opac}} \sim 1$ MeV is about 10 sec. This is an order of magnitude larger than without NT and of the same order as the duration long gamma ray bursts.

1. Introduction

Gamma ray bursts (GRBs) are among the most intriguing phenomena in the Universe, see\(^1\) and references therein. If the energy is emitted isotropically, the measured energy release is of the order of $10^{53} \div 10^{54}$ erg and it is a puzzle to explain the engine of a GRB. However, there is now a compelling evidence that the gamma ray emission is not isotropic, but displays a jet-like geometry. When the emission is collimated within a narrow beam a smaller energy, of the order of $10^{52}$ erg, would be sufficient for the GRBs\(^2\) but their sources are not yet understood. There is growing evidence for

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a connection of GRBs to supernovae now from emission features in some GRB afterglows, e.g. GRB 990707, GRB 991216, GRB 000214 and, most recently GRB 030329. As in the realm of a supernova explosion a compact star is likely to be born, it has been conjectured (see and references therein) that a phase transition from hadronic to deconfined quark matter might power the GRB. However, although the energy release might be in the right order of magnitude, the collapse timescale is too short (∼ several ms) to explain long GRBs with a duration of several tens of seconds. Recently, it has been suggested that the deconfinement transition in a compact star might be an example for a nucleation process of quark matter droplets which is a quantum tunneling process between metastable states, with a sufficient delay, depending on the surface tension of the quark matter droplet. This approach has been criticized since during the supernova collapse the protoneutron star can be heated up to temperatures of the order of the Fermi energy $T \sim \epsilon_F \approx 30 \div 40$ MeV so that the thermal fluctuations would dominate over quantum ones and make the phase transition sufficiently fast without the delay claimed in Ref. 7.

In the present contribution we consider the cooling evolution of a hot protoneutron star above the neutrino opacity temperature $T_{\text{opac}} \sim 1$ MeV, so that the neutrino mean free path is by orders of magnitude smaller than the size of the star. As it has recently been estimated and also reported at this conference, the neutrino untrapping transition occurring when the star cools below $T_{\text{opac}}$ might serve as an engine of a GRB. The question to be considered here is whether the energy release by neutrino emission can be sufficiently delayed due to neutrino trapping so that the typical duration of a long GRB could be explained.

2. Early cooling evolution

During the collapse of the progenitor star the density increases in its very interior from the densities of the iron core to those at and above the deconfinement transition. For this huge interval of densities, part of which we display in Fig. 1, matter can undergo several phase transitions. During these processes, like leptonization and deleptonization, neutrinos and antineutrinos are produced in weak interactions which eventually could also be trapped during the early stages of the evolution when the temperatures are expected to be much higher than $T_{\text{opac}}$. The cooling process for such a PQS is investigated in this contribution, where we use a simplified model of a homogeneous PQS structure and an approximate global thermal evolution.
If the star cools below $T_{\text{opac}}$ by surface-radiation, neutrinos could escape in a sudden outburst. For brevity, saying neutrino means both neutrino and antineutrino.

The loss of energy in a homogeneous system due to emission is given by

$$\frac{dU(T)}{dt} = -\epsilon_{\nu}(T) \cdot V .$$  \hspace{1cm} (1)

Here the photon emissivity has been neglected since neutrinos dominate the cooling evolution of a PQS for temperatures well above $10^6$ K. For the cooling behaviour of a star from a given initial-temperature $T_i$ to a final temperature $T_f$ with the luminosity $L(T) = -\epsilon_{\nu}(T) \cdot V$ follows

$$\Delta t = - \int_{T_i}^{T_f} \frac{C_{\nu}(T) \cdot dT}{L(T)} .$$  \hspace{1cm} (2)

The luminosity $L(T) = L_{\nu}^{\nu}(T) + L_{\nu}^{\nu}(T)$ is explained more in detail in Section 3 and the specific heat $C_{\nu}(T)$ can be derived from the thermal energy $U(T)$ for relativistic quark matter $^{12}$

$$C_{\nu}(T) = \frac{dU}{dT} = 1.8 \times 10^{48} \left( \frac{M}{M_\odot} \right) \left( \frac{n_B}{n_0} \right)^{-1/3} T_9 \text{ erg.}$$  \hspace{1cm} (3)
Here $M$ is the mass of the star in units of the solar one and $n_B$ is the baryon density of the star for a homogeneous mass distribution in units of the nuclear saturation density $n_0 = 0.16 \text{ fm}^{-3}$. For the temperature we use the standard notation $T_9 = T/10^9 \text{ K}$.

The emissivity for the direct URCA process in normal quark matter is given by

$$
\epsilon_{\text{URCA}}^\nu(T) \simeq \frac{914}{315} \pi^2 G_F^2 \cos^2 \theta_c \alpha_s n_B (3Y_d Y_u Y_e)^{\frac{1}{3}} T^6,
$$

where $G_F$ is the Fermi constant of the weak interaction, $\alpha_s$ is the strong coupling constant and $\theta_c$ the Cabbibo angle. We have introduced the fractions of the particle species $i$ as $Y_i = n_i/n_B$ and the baryon density in terms of up and down quark densities is $n_B = (n_u + n_d)/3$. The neutrino mean free path (MFP) has the expression

$$
\lambda(T) = \frac{(6\pi)^{\frac{1}{2}}}{12 G_F^2 \cos^2 \theta_c Y_u^Y_e} n_B^{-\frac{1}{3}} \left[ 1 + \frac{1}{2} \left( \frac{3Y_e}{Y_u} \right)^{\frac{1}{3}} + \frac{1}{10} \left( \frac{3Y_e}{Y_u} \right)^{\frac{2}{3}} \right]^{-1}
$$

$$
\times [(E_\nu - \mu_\nu)^2 + (\pi T)^2]^{-1}.
$$

Using the PQS matter constraints of charge neutrality $\frac{2}{3}n_u - \frac{1}{3}n_d - n_e = 0$ and $\beta$-equilibrium for the case of trapped neutrinos $\mu_\nu = \mu_u + \mu_e - \mu_d$, we can express all particle fractions $Y_i$ via $Y_e$. In our model calculation we choose $Y_e = 0.001$ and approximate $E_\nu \simeq T$. For the above choice of parameters, the temperature dependence of the MFP is shown in Fig. 2 and the emissivity in Fig. 3, respectively.

### 3. Emissivity and luminosity of PQS

The emissivity $\epsilon_{\nu}^{\text{URCA}}$ for the direct URCA-process in quark-matter Eq. (4) has to be modified for temperatures, at which the star is opaque to neutrinos. Due to the trapping of the neutrinos their emissivity is modified by a factor which takes into account the probability that the neutrino created at a distance $r$ from the center can leave the star in the direction given by the angle $\alpha$. The effective emissivity is given by a product of the emissivity for the direct URCA process and an exponential suppression factor

$$
\bar{\epsilon}_\nu(r, \alpha; T) = \exp \left[ -l(r, \alpha)/\lambda(T) \right] \cdot \epsilon_{\nu}^{\text{URCA}}(T),
$$

where $l(r, \alpha)$ is the distance from the neutrino creation point to the star surface, which for a spherically symmetric star with radius $R$ is given by

$$
l(r, \alpha) = \sqrt{R^2 - r^2 \sin^2 \alpha} - r \cos \alpha.
$$
Figure 2. The neutrino MFP as a function of the temperature for given baryon density and electron fraction.

We average over all possible neutrino directions

$$\bar{\bar{\varepsilon}}_\nu(r; T) = \frac{1}{\pi} \int_0^\pi d\alpha \, \bar{\varepsilon}_\nu(r, \alpha; T),$$

and integrate over all distances $r$ up to the star radius $R$ in order to obtain the total luminosity for neutrino emission from the star volume

$$L^V_{\nu}(T) = 4\pi \int_0^R dr \, r^2 \cdot \bar{\varepsilon}_\nu(r; T).$$

As long as the temperatures are high enough, $T \gtrsim 1$ MeV, there is a spherical inner star region, from where practically no neutrinos escape so that their number is quasi conserved and can be defined by a finite chemical potential $\mu_{\nu}$. This region extends up to a distance $R_S$ from the center. The radius $R_S$ of the neutrinosphere is a function of the temperature and moves towards the center during the cooling evolution, see Fig. 4. In calculating the bulk neutrino luminosity of a PQS during the trapping era, we can restrict the integration in Eq. (9) to the region between the neutrinosphere
Figure 3. Temperature dependence of the neutrino emissivity for the URCA process for given baryon density and electron fraction.

Figure 4. Evolution of the neutrinosphere.

and the surface of the star. Besides the bulk luminosity we have additional neutrino radiation just from the neutrinosphere which can be taken into
account by the generalized blackbody radiation formula

\[
L^O_\nu(T) = 4\pi R_S^2 \cdot \left( \frac{\mu_\nu^4}{4\pi^2} + \frac{\mu_\nu^2 T^2}{2} + \frac{7\pi^2 T^4}{60} \right), \tag{10}
\]

which we denote as inner surface luminosity. From the evolution of \(R_S\) with time we can characterize the untrapping transition of neutrinos as a burst-type phenomenon or a smooth fading. In Fig. 5 we compare the temperature dependence of the bulk and inner surface neutrino luminosities. These results show that the trapping of the neutrinos changes the luminosities by about 6 orders of magnitude within the trapping regime. Moreover, for the trapping case, in contrast to the untrapped bulk emission, the bulk luminosity has a maximum at \(10^{53}\) erg/s for temperatures around 15 MeV. Due to this particular behavior of the bulk luminosity in the neutrino trapping regime we expect that for initial temperatures much higher than 30 MeV there is not only a quantitative change in the cooling evolution but rather a qualitative change in the temporal evolution of the energy release.

![Figure 5](image-url)
4. Results

In Fig. 6 we show the cooling curves of a PQS for an initial temperature of \( T_i = 30 \) MeV and a star radius of \( R = 12 \) km. The solid line corresponds to a cooler in the trapping regime including all effects discussed above. The other curves correspond to limiting cases, in particular to the case without trapping (dotted line), the case with trapping but without surface emission (dashed line) and the emission from the inner sphere only (dash-dotted line). The comparison shows that at the vicinity of the total untrapping regime for \( T = 0.6 \) MeV the time delay of the cooling with trapping amounts to a factor of ten. If one will neglect the inner surface emission of the neutrinos, then the neutrino release will not only be delayed but also occur within a sudden burst.

5. Outlook

The investigation of the effects of neutrino trapping on PQS evolution is only in its beginning. We have outlined a simple model for the study of spherical neutrino emission from a hot PQS with and without trapping.
Detailed investigations have to be conducted in order to make firm conclusions whether the hot neutrino trapping scenario could shed light into the mysteries of GRBs and the GRB supernova connection. We underline two observations made in this report:

- The main thermal energy of the star is released in a time interval, which is of the order of the duration of long GRB’s (∼10 s).
- The amount of energy which can be released in the cooling of a homogeneous PQS depends much on the initial temperature which is unknown and might for the PQS scenario be up to one order of magnitude larger than for the canonical protoneutron star scenario.

This latter observation can have significant implications for the early cooling evolution after a supernova collapse due to the strong temperature dependence of the dominating URCA process on the one hand and the large effective absorption of bulk emissivity on the other. Note that we have omitted here the possible effects of finite thermal conductivity which could make the separation of the neutrinosphere from the bulk emission zone even stronger and enhance the eventual temporal structure in the cooling evolution. First estimates show that the neutrino release can occur within a burst 10 and provided the conversion process to gamma rays is effective enough 14, an interesting PQS-GRB scenario emerges which can include a beaming mechanism due to the formation of a vortex lattice in a strongly magnetized superconducting PQS 15.

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