

Neutrino and Electron-positron Pair Emission from Phase-induced Collapse of Neutron Stars to Quark Stars

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Abstract

We study the energy released from phase-transition induced collapse of neutron stars, which results in large amplitude stellar oscillations. To model this process we use a Newtonian hydrodynamic code, with a high resolution shock-capturing scheme. The physical process considered is a sudden phase transition from normal nuclear matter to a mixed phase of quark and nuclear matter. We show that both the temperature and the density at the neutrinosphere oscillate with time. However, they are nearly 180° out of phase. Consequently, extremely intense, pulsating neutrino/antineutrino and leptonic pair fluxes will be emitted. During this stage several mass ejecta can be ejected from the stellar surface by the neutrinos and antineutrinos. These ejecta can be further accelerated to relativistic speeds by the electron/positron pairs, created by the neutrino and antineutrino annihilation outside the stellar surface. We suggest that this process may be a possible mechanism for short Gamma-Ray Bursts.

1 Introduction

Recently, by using simulations performed with the Newtonian numerical code introduced in [1], it was shown that the resulting quark star, produced by the phase transition induced collapse of a neutron star, will undergo a series of oscillations. The collapse process with a conformally flat approximation to general relativity was also

simulated in [2]. The works of [1, 2] focus on the gravitational wave signals emitted by the collapse process.

It is the purpose of the present paper to consider another important implication of this result, namely, the effect of the oscillations of the newly formed quark star on the neutrino emission. The oscillations can enhance the neutrino emission rate in a pulsating manner, and the neutrinos are emitted in a much shorter time scale. Moreover, through the process of neutrino-antineutrino annihilation, a large amount of electron-positron pairs is also produced. Therefore the neutron-quark phase transition in compact objects may be the energy source of GRBs [3]. Such a model can also explain the lack of detection of a neutron star or pulsar formed in the SN 1987A [4], by assuming that the newly formed neutron star at the center of SN 1987A underwent a phase transition after the neutrino trapping timescale (~ 10 s). Consequently, the compact remnant of SN 1987A may be a strange quark star, which has a softer equation of state than that of neutron star matter. Such a phase transition can induce stellar collapse and result in large amplitude stellar oscillations. Extremely intense pulsating neutrino fluxes, with submillisecond period and with neutrino energy (greater than 30 MeV), can be emitted because the oscillations of the temperature and density are out of phase almost 180° . If this is true, the current X-ray emission from the compact remnant of SN 1987A will be lower than 10^{34} erg s $^{-1}$, and it should be a thermal bremsstrahlung spectrum for a bare strange star with a surface temperature of around ~ 107 K.

2 Description of the phase transition and of the equations of state

The numerical code is based on the three-dimensional numerical simulation in Newtonian hydrodynamics and gravity. The quark matter of the mixed phase is described by the MIT bag model and the normal nuclear matter is described by an ideal fluid EOS. This code has been used to study the gravitational wave emission from the phase-induced collapse of the neutron stars [1], where a detailed discussion can be found. In the simulations, we introduced a very low density atmosphere outside the star. The "artificial" atmosphere is not physical, but it is important for the stability of the hydrodynamical code. This is due to the problem that the hydrodynamical codes cannot in general handle vacuum regions where the density is zero. In order to avoid a significant influence of the atmosphere on the dynamics of the physical system, it is necessary to choose the density of the atmosphere ρ_{atm} to be much smaller than the density scale of interest. For the results reported in this paper, we set ρ_{atm} to be 3×10^9 g/cm 3 .

In our simulations, we will not simulate the phase transition process. Instead, we assume that a fast phase transition has happened (e.g., via a detonation mode)

so that the initial neutron star has converted to a quark star in a timescale shorter than the dynamical timescale of the system. We assume that the normal matter inside the initial neutron star has suddenly changed to quark matter at $t = 0$. This is achieved by changing the EOS at $t = 0$ after the initial hydrostatic equilibrium neutron star has been constructed. We then simulate the resulting dynamics of the system triggered by the collapse.

The equation of state (EOS) for neutron stars is highly uncertain. We could try all possible existing realistic EOS in our study. However, the main purpose of this paper is to demonstrate that during the phase-transition induced collapse of a neutron star extremely intense, pulsating and very high energy neutrinos can be emitted. The effect is governed mainly by the amount of pressure reduction after the phase transition as compared to the initial neutron star model. For simplicity we will use a polytropic EOS for the initial equilibrium neutron star:

$$P = k_0 \rho^{\Gamma_0}, \quad (1)$$

where k_0 and Γ_0 are constants. On the initial time slice, we also need to specify the specific internal energy ϵ . For the polytropic EOS, the thermodynamically consistent ϵ is given by

$$\epsilon = \frac{k_0}{\Gamma_0 - 1} \rho^{\Gamma_0 - 1}. \quad (2)$$

Note that the pressure in Eq. (1) can also be written as

$$P = (\Gamma_0 - 1) \rho \epsilon. \quad (3)$$

In this paper we use a mixed phase EOS to mimic a quark star core covered by normal nuclear matter. This EOS model consists of two parts: (i) a mixed phase of quark and nuclear matter in the core at density higher than a certain critical value ρ_{tr} (quark seeds can spontaneously produce everywhere when $\rho \geq \rho_{tr}$) (ii) a normal nuclear matter region extending from $\rho < \rho_{tr}$ to the surface of the star. A more detailed discussion about such hybrid quark stars can be found in [1]. Explicitly, the pressure is given by

$$P = \begin{cases} \alpha P_q + (1 - \alpha) P_n, & \text{for } \rho > \rho_{tr} \\ P_n, & \text{for } \rho \leq \rho_{tr}, \end{cases} \quad (4)$$

where

$$P_q = \frac{1}{3} (\rho + \rho \epsilon - 4B), \quad (5)$$

is the pressure contribution of the quark matter,

$$P_n = (\Gamma_n - 1) \rho \epsilon, \quad (6)$$

and

$$\alpha = \begin{cases} (\rho - \rho_{tr})/(\rho_q - \rho_{tr}), & \text{for } \rho_{tr} < \rho < \rho_q, \\ 1, & \text{for } \rho_q < \rho, \end{cases} \quad (7)$$

is defined to be the scale factor of the mixed phase [1]. Γ_n is not necessarily equal to Γ_0 . As for the quark matter we have assumed that it is described by the MIT bag model. It should be noticed that P_q is not in the usual form of $P = (\rho_{\text{tot}} - 4B)/3$, where ρ_{tot} is the (rest frame) total energy density, and B is the bag constant. It is because in our Newtonian simulations, we use the rest mass density ρ and specific internal energy ϵ as fundamental variables in the hydrodynamics equations.

The total energy density ρ_{tot} , which includes the rest mass contribution, is decomposed as $\rho_{\text{tot}} = \rho + \rho\epsilon$. We choose $\Gamma_n < \Gamma_0$ in our simulations to take into account the possibility that the nuclear matter may not be stable during the phase transition process, and hence some quark seeds could appear inside the nuclear matter, or the convection, which can occur during the phase transition process, can mix some quark matter with the nuclear matter. In the presence of the quark seeds in the nuclear matter, the effective adiabatic index will be reduced. The possible values of $B^{1/4}$ range from 145 MeV to 190 MeV [5, 6, 7, 8]. For $\rho > \rho_q$, the quarks will be deconfined from nucleons. The value of ρ_q is model dependent; it could range from 4 to 8 ρ_{nuc} [8, 9, 10], where $\rho_{\text{nuc}} = 2.8 \times 10^{14} \text{ g cm}^{-3}$ is the nuclear density.

The properties of a mixed quark-hadron phase and its implications for hybrid star structure were considered in [11]. In this study it was assumed that charge neutrality must be enforced only as an overall constraint, and not separately on each of the phases. In the mixed phase the fraction χ of the volume occupied by the quark phase can be taken as the basic independent variable, being more convenient than the baryon density. The pressures of the two phases in equilibrium are equal, but vary with the quark fraction. Once the properties of the two phases are known, with the use of the relationships between the quark chemical potentials and the independent conserved quantities like baryon number and electron charge, the equation of state of the matter in the mixed phase can be obtained. In Fig. 1 we present the equation of state of the mixed phase obtained in [11] for a compression modulus $K = 240 \text{ MeV}$ and an effective mass at saturation density of $m^*/m = 0.78$, and the equation of state Eq. (4) used in the present simulation, respectively.

In the simulations, we choose $\Gamma_0 = 2$, $\Gamma_n = 1.85$, $B^{1/4} = 160 \text{ MeV}$ and $\rho_q = 9\rho_{\text{nuc}}$. The transition density ρ_{tr} is defined to be at the point where P_q vanishes initially.

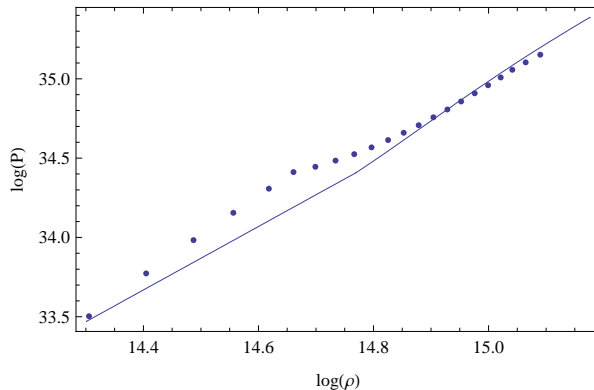


Figure 1: Comparison of the equation of state of the mixed quark-hadron phase proposed in [11] for $K = 240$ MeV and effective mass $m^*/m = 0.78$ (dotted curve), and Eq. (4), the equation of state if the mixed phase used in the present simulations (solid curve).

3 Emission of neutrinos and e^\pm pairs

The neutrino luminosity is given by [12],

$$L_\nu = 4\pi r^2 c \frac{1}{2\pi\hbar^2} \int \frac{E_\nu d^3\mathbf{p}_\nu}{1 + \exp(E_\nu - \mu_\nu/kT_\nu)}, \quad (8)$$

where μ_ν is the neutrino chemical potential. Taking $\mu_\nu = 0$, the neutrino luminosity emitted from the neutrinosphere is given by $L_\nu = 7\pi R_\nu^2 a c T_\nu^4 / 16$, where $a = 4\sigma/c$ is the radiation constant, σ is the Stefan-Boltzmann constant, and T_ν is the temperature of the neutrinosphere. If we assume equal luminosities for neutrinos and antineutrinos, the combined luminosity for a single neutrino flavor is

$$L_{\nu, \bar{\nu}} = L_\nu + L_{\bar{\nu}} = \frac{7}{8}\pi R_\nu^2 a c T_\nu^4. \quad (9)$$

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter [15]. Although different flavor neutrinos have different R_ν , yet they have approximately the same value of luminosity for all flavors [16, 17]. Therefore the total luminosity is around three times of a single neutrino flavor luminosity

$$L = L_{\nu_e, \bar{\nu}_e} + L_{\nu_\mu, \bar{\nu}_\mu} + L_{\nu_\tau, \bar{\nu}_\tau} = \frac{21}{8}\pi R_\nu^2 a c T_\nu^4. \quad (10)$$

Using R_ν and T_ν obtained from the last Section, we compute the the neutrino luminosity as a function of time. The results are shown in Fig. 2.

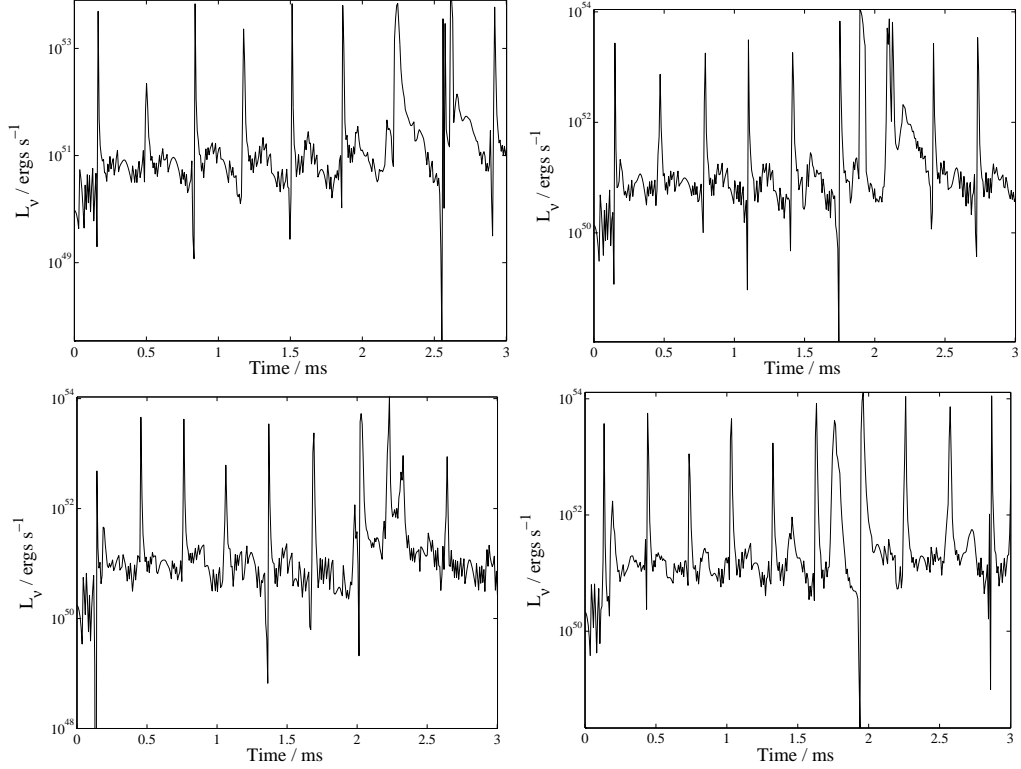


Figure 2: Neutrino luminosity versus time for $M = 1.55M_{\odot}$, (left upper figure), $M = 1.7M_{\odot}$, (right upper figure), $M = 1.8M_{\odot}$, (left lower figure), $M = 1.9M_{\odot}$, (right lower figure).

The peak luminosities range from 10^{52} to 10^{54} ergs/s; the pulsating period of the luminosity is the same as that of the temperature and of the density.

Neutrinos and antineutrinos can become electron and positron pairs via the neutrino and antineutrino annihilation process ($\nu + \bar{\nu} \rightarrow e^{-} + e^{+}$). The total neutrino and antineutrino annihilation rate can be given as follows [13, 14]

$$\dot{Q}_{\nu\bar{\nu}\rightarrow e^{\pm}} = \frac{7G_F^2\pi^3\zeta(5)}{2c^5h^6}D[kT_{\nu}(t)]^9\int_{R_{\nu}}^{\infty}\Theta(r)4\pi r^2dr \quad (11)$$

$$= \frac{7G_F^2D\pi^3\zeta(5)}{2c^5h^6}\frac{8\pi^3}{9}R_{\nu}^3(kT_{\nu})^9, \quad (12)$$

where $\Theta(r) = 2\pi^2(1-x)^4(x^2+4x+5)/3$, $x = \sqrt{1-R_{\nu}^2/r^2}$, $T_{\nu}(t)$ is the temperature at the neutrinosphere at time t , $G_F^2 = 5.29 \times 10^{-44}$ is the Fermi constant, ζ is the Riemann zeta function, and D is a numerical value depending on the pair creation processes (e.g. experimental results indicate that $D_1 = 1.23$ for $\nu_e\nu_{\bar{e}}$ and $D_2 = 0.814$

for $\nu_\mu \nu_\mu$ and $\nu_\tau \nu_\tau$). To obtain the total neutrino annihilation rate from all species, $\nu_e \nu_e$, $\nu_\mu \nu_\mu$ and $\nu_\tau \nu_\tau$, we sum up the energy rate for each single flavor,

$$\begin{aligned}\dot{Q} &= \dot{Q}_{\nu_e \bar{\nu}_e} + \dot{Q}_{\nu_\mu \bar{\nu}_\mu} + \dot{Q}_{\nu_\tau \bar{\nu}_\tau} \\ &= \frac{28G_F^2 \pi^6 \zeta(5)}{9c^5 h^6} (D_1 + 2D_2) R_\nu^3 (kT_\nu)^9.\end{aligned}\quad (13)$$

Fig. 3 shows the rate of energy carried away by the electron/positron pairs produced through neutrino annihilation, which varies from $\sim 10^{51}$ ergs/s to $\sim 10^{53}$ ergs/s.

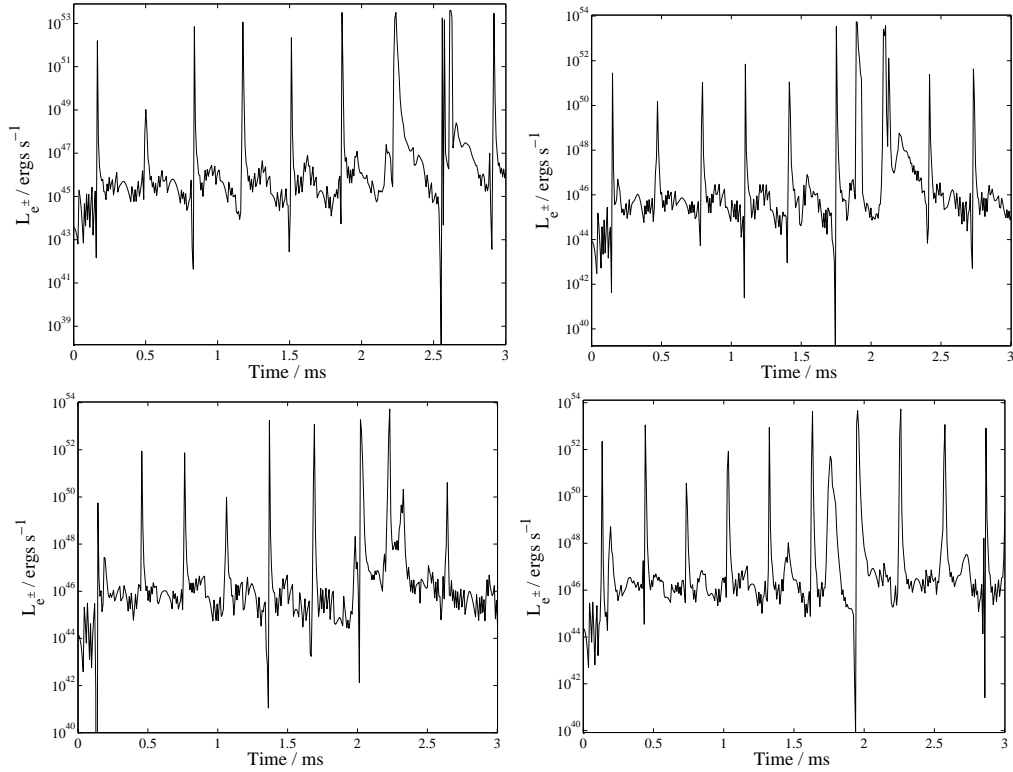


Figure 3: Electron-positron luminosity versus time for $M = 1.55M_\odot$, (left upper figure), $M = 1.7M_\odot$, (right upper figure), $M = 1.8M_\odot$, (left lower figure), $M = 1.9M_\odot$, (right lower figure).

It is interesting to note that almost all neutrinos can be annihilated into electron-positron pairs at the peak because of the extremely high density and high energy of the neutrinos. In particular the rest mass of the electrons/positrons is much smaller than kT_ν .

4 Discussions and final remarks

In this paper we have studied the possible consequences of the phase-induced collapse of neutron stars to strange stars. We have found that both the density and the temperature inside the star will oscillate with the same period, but almost 180° out of phase, which will result in the emission of intense pulsating neutrinos and pairs. We want to point out that the intense pulse neutrino luminosity can be maintained due to the oscillatory fluid motion, which can carry thermal energy directly from the stellar core to the surface. This process can replenish the energy loss of neutrino emission much quicker than the neutrino diffusion process. A large fraction of the neutrino energy, roughly $(1-1/e)$, will be absorbed by the matter very near the stellar surface. When this amount of energy exceeds the gravitational binding energy, some mass near the stellar surface will be ejected, and this mass will be further accelerated by absorbing pairs created from the neutrino and antineutrino annihilation processes outside the star. Although matter will be ejected periodically, each ejecta can have different masses and Lorentz factors, and therefore the intrinsic period could not be observed. We suggest that the collisions among these ejecta may produce short GRBs. Our numerical simulations are simulating a spherically symmetric and non-rotating collapsing stellar object, and they also do not contain magnetic fields. Therefore the radiation emission produced in this model is isotropic. However, a realistic neutron star should have finite angular momentum and strong magnetic field, and hence these two factors could produce asymmetric mass ejection. This effect will be considered in future work.

The phase-transition from a neutron star to a strange star was simulated in [18], with the conclusion that this process is most likely not a gamma-ray burst mechanism. They mimic the phase-transition by the arbitrary motion of a piston deep within the star, and they have found that the mechanic wave will eject $\sim 10^{-2}M_\odot$ baryons, which causes the baryon contamination for the gamma-ray bursts. In our simulations, we assume a sudden change of equation of state to mimic the phase-transition, and we use the Newtonian hydrodynamic code to study the response of the stellar interior after such a sudden change of the EOS. In our simulations we find that the mass ejection by the motion of the fluid is very small. We estimate that the major mass ejection would result from the heating of neutrinos and pairs on the stellar crust, which is not modeled in the simulations. Our total energy output and total mass in ejecta are close to that of [18]. However, the neutrino energy injection is pulsating, and hence the mass ejection is also pulsating. The mass of individual ejecta range from $\sim 10^{-9}$ to $\sim 10^{-4}M_\odot$, with output energy in the range of 10^{48} to 10^{50} ergs. Therefore, some ejecta cannot be relativistic, and they cannot contribute to GRBs. However, there are still many relativistic ejecta in each simulation model, which can have Lorentz factors >100 , and with a total energy of $\sim 10^{50} - 10^{51}$ ergs. This could be a possible mechanism for short GRBs.

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