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# Gravitational wave emission during the transition to strange stars

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We present a series of axisymmetric, magneto-hydrodynamical simulations for the rotational core collapse of a massive star accompanying the QCD phase transition. To elucidate the implications of a phase transition against a supernova, we investigate the waveforms of gravitational wave derived from the quadrupole formula that includes the contributions from the electromagnetic fields. We adopt a phenomenological equation of state above the nuclear matter density $\rho_0$ that includes two parameters to change the hardness of the matter before the transition. We assume that the first order phase transition is the conversion of bulk nuclear matter to a chirally symmetric quark-gluon phase described by the MIT bag model. In most models with the phase transition, the first peak amplitudes are higher by a few percents to nearly ten percents than those without the transition. However, it is found that under the condition of the very strong differential rotation, the height of the peak becomes lower by several percents if the phase transition is included. In the paper, we show the typical models of our calculations.

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## 1. Introduction

It has been presented that the quark matter might appear during supernova explosions [1, 2] or the transition of a neutron star to a quark star [3, 4, 5]. In particular, it is very important to model the core-collapse supernova with the QCD phase transition since supernovae with very large explosion energies are responsible to some classes of gamma-ray bursts [6].

The gravitational wave astronomy becomes realistic in these days. The interferometer projects, planned TAMA, GEO, and LIGO, have started already [7]. Gravitational waves from the rotational core collapse of massive star are studied by many researchers [8, 9, 12, 13, 14]. Therefore, it must be crucial to examine how the phase transition influences the gravitational wave form.

In the present paper we investigate the effects of the QCD phase transition on the gravitational radiation during the supernova explosion until about 90 ms from the collapse using the two-dimensional MHD code.

## 2. Input physics and initial condition

### 2.1 Input physics

The numerical method in this paper is based on the ZEUS-2D code [15]. We take into account the general relativistic correction [16] to the Newtonian gravity. To compute the gravitational waveforms from the rotating magnetized stellar core, we follow the method of the quadrupole formula [12]. We assume that the distance from the observer ($R$) is 10 kpc in the direction of the equator ($\alpha = \pi/2$). We neglect neutrino processes.

Since there does not exist any reliable EOS that describes the QCD phase transition, we follow the method adopted in Gentile et al. (1993) [2] and the references [3, 17]. We assume that the first order phase transition occurs during the collapse beyond some critical density, which has been suggested in multicomponent system of quark-gluon plasma [18]. We set the QCD coupling constant $\alpha_s = 0$ in two models u-Mm and d-Mm, which indicates that the coexistence phase between the baryon and quark is the widest in the density region: This choice helps us evaluate the effects of the phase transition maximally [2]. To estimate the effects of coupling constant, we calculate other two models u-Mma and d-Mma set on $\alpha_s = 0.25$.

In the baryon phase, we adopt the phenomenological EOS of BCK (Baron, Cooperstein, & Kahana 1985b [19]) that includes two parameters of the incompressibility $K$ and the adiabatic index $\Gamma$ to express the degree of the hardness of matter above the saturation density $\rho_0$. We set $K =$ 220 MeV, $\Gamma = 3$. We note that recent measurements give the constraints on the incompressibility $210 \leq K \leq 270$ MeV [20, 21, 22]. Therefore the adopted value of $K = 220$ MeV is consistent with this measurement. The EOS of BCK is used above $\rho_0$ with the pressures of electrons and photons included in the regions [2]. Since we focus on the behaviour of the EOS above $\rho_0$, we use the phenomenological EOS of Yamada & Sato (1991) [23] below $\rho_0$ in all our models.

As for the criterion of the phase transition, we impose the condition that the pressure $P$ and chemical potential $\mu$ between the baryon and quark phase are the same. We assume that the transition starts at $\rho_1 = 5 \times 10^{14}$ g cm$^{-3}$ for the baryon phase. Then, the end point of the transition ($\rho_2$) and $B$ are determined analytically from the condition of $P = P_1$, $\mu = \mu_1$, and $\alpha_s$ for the quark phase : $\rho_2$ and/or $B(\rho_1, P_1, \mu_1, \alpha_s)$. We obtain $\rho_2 = 7.01(10^{14}$g cm$^{-3})$, $B^{1/4} = 163.8$(MeV), and

$\mu = 949$(MeV) for $\alpha = 0$. For the another parameter $\alpha = 0.25$, we get $\rho_2 = 6.00(10^{14}$g cm$^{-3})$, $B^{1/4} = 157.3$(MeV), and $\mu = 953$(MeV). While we get the reasonable value about $\mu$, $\rho_1$ and $\rho_2$ are rather low compared to the suggestion from the QCD theory, which is based on lattice QCD calculations : the transition occurs at $\mu \geq 1000$ MeV and $\rho \geq 10^{15}$ g cm$^{-3}$ [24].

### 2.2 Initial condition

We adopt the presupernova model of 13 $M_\odot$ that has the iron core (Fe-core) of 1.2 $M_\odot$. We note that the size of the Fe-core is similar for massive stars of $M \leq 70\ M_\odot$ [25]. Since small mass differences before the bounce do not influence the gravitational waves amplitude (GWA) [26], we use only this model.

For the initial angular velocity distribution, we adopt the $shell-type$ rotational law:

$$\Omega(r) \,=\, \Omega_0 \times \frac{R_0^2}{r^2+R_0^2},$$

where $\Omega(r)$ is the angular velocity and $r$ is the radius. Both $\Omega_0$ and $R_0$ are model constants. We regard the model with $R_0 = 10^3$ km as uniformly rotating, since the radius of Fe core is $\sim 10^3$ km. In most initial models, the initial magnetic field is assumed to be constant, $B_0$, which is poloidal and parallel to the rotational axis in all computational domain. For the only two models in Table 1, we assume that the initial magnetic field is purely toroidal :

$$B_\phi(r) \,=\, B_0 \times \frac{R_0^2}{r^2+R_0^2},$$

where $B_\phi(r)$ is toroidal component of the magnetic fields, and $B_0$ is a constant.

In the paper, we present core-collapse simulations of 8 models which are given in Table 1. The characters in the left hand side for each column indicate the initial condition concerning the magnetic fields and rotations: s (spherical), u (weak uniform rotation and weak magnetic field), d (strong differential rotation and strong magnetic filed), b (strong differential rotation and very strong magnetic field of the $shell-type$ law). The characters after the hyphen indicate the adopted EOSs. The inclusion of the QCD phase transition is indicated by 'M': B (BCK without the phase transition), and M (MIT bag model with the phase transition).

## 3. Numerical results and brief discussions

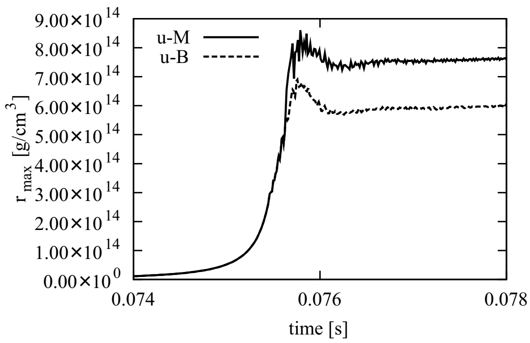
In most models, the explosion energy ($E_{exp}$) considering the phase transition is larger by some 10 percents. In particular, the increase in $E_{exp}$ for the spherical (s-) model amounts to 33%, which is consistent with the previous researches [1, 2]. The magnetic field affected by the transition is not so impotant to GWA. In this paper, QCD color-superconductivity rerated to the strong magnetic field is not considered. There is a possibility that the effect may change our results, since changes in ferro-magnetism affects the explosion mechanism[27, 28].

### 3.1 Effects of the phase transition under the nearly uniform rotation

We will first show the effects of the phase transition on the GWA under the nearly uniform rotation of initial models. We find that the GWAs are larger from a few percents to about ten percents by considering the phase transition for "u-" models in Table 1.

**Table 1:** Model parameters and maximum GWAs $|h^{TT}|_{max}$ as the results. For two models of b-B and b-M, the shell-type distribution of the magnetic field $B_\phi = B_0 \times R_0^2/(r^2+R_0^2)$ is assumed.

| Model | $\alpha_s$ | $R_0$ (km) | $T/\lvert W\rvert_{\rm ini}$ (%) | $E{\rm m}/\lvert W\rvert_{\rm ini}$ (%) | $\Omega_0$ ($s^{-1}$) | $B_0$ (G) | $\lvert h^{TT}\rvert_{max}$ ($10^{-20}$) |
|---|---|---|---|---|---|---|---|
| s-B | - | - | - | - | - | - | - |
| s-M | 0 | - | - | - | - | - | - |
| u-B | - | $10^3$ | 0.1 | $10^{-3}$ | 2.3 | $6.7\times10^{10}$ | 0.31 |
| u-Ma | 0.25 | $10^3$ | 0.1 | $10^{-3}$ | 2.3 | $6.7\times10^{10}$ | 0.32 |
| u-M | 0 | $10^3$ | 0.1 | $10^{-3}$ | 2.3 | $6.7\times10^{10}$ | 0.34 |
| d-B | - | $10^2$ | 0.5 | $10^{-1}$ | 58.8 | $6.7\times10^{11}$ | 3.03 |
| d-Ma | 0.25 | $10^2$ | 0.5 | $10^{-1}$ | 58.8 | $6.7\times10^{11}$ | 2.79 |
| d-M | 0 | $10^2$ | 0.5 | $10^{-1}$ | 58.8 | $6.7\times10^{11}$ | 2.72 |
| b-B | - | $10^2$ | 0.5 | $10^{-1}$ | 58.8 | $1.3\times10^{14}$ | 2.96 |
| b-M | 0 | $10^2$ | 0.5 | $10^{-1}$ | 58.8 | $1.3\times10^{14}$ | 2.69 |



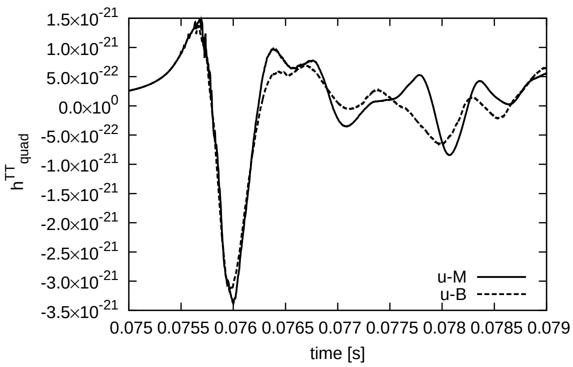




**Figure 1:** the maximum density and waveform of uniform rotational (u-) models.

Fig. 1 shows the time dependence of the maximum density and the GWA for "u-" models. The maximum density of the model with the phase transition (the model of u-M) is always larger than that without the transition (the model of u-B). Since the transition causes the increase in the density similar to the effect of soft EOS, we get larger amplitude of the gravitational wave by considering the transition [14]. If the coupling constant $\alpha_s = 0.25$, the coexistence area of two phases becomes small, and the effect on GWA by the transition becomes small (See Table 1).

### 3.2 Effects of phase transition under the differential rotation

If the initial rotation is nearly uniform, $|h^{\rm TT}|_{\rm max}$ is larger in proportional to $\rho_{\rm max}$ as described in the previous subsection. However, $|h^{\rm TT}|_{\rm max}$ does not keep pace with the maximum density for the strong differential rotation. Fig. 2 shows the time dependences of the maximum density and the GWA. The results for d-M and d-B indicate that $|h^{\rm TT}|_{\rm max}$ becomes small if the phase transition is included, while the model with the transition has the larger maximum density.

This feature is not so strange. The similar tendency has been discussed "type III" wave form [14]. They have shown that soft EOS decreases the first peak of GWA for the strong dif-

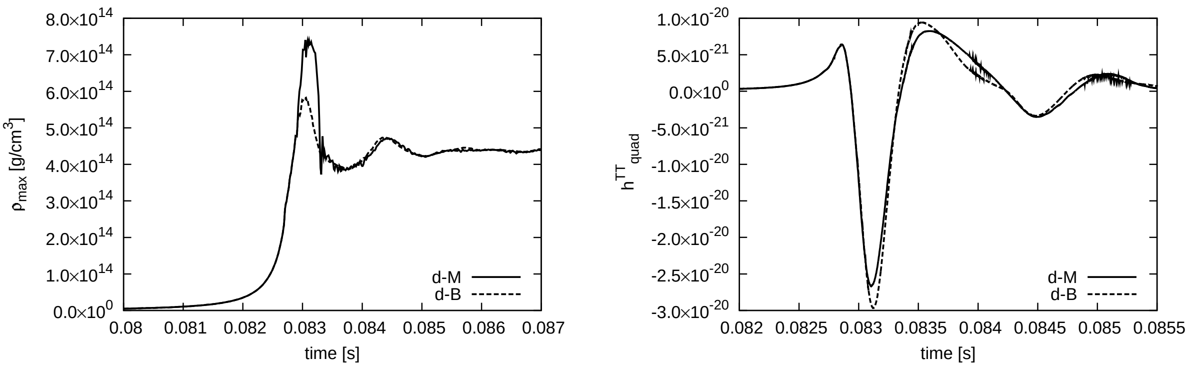



**Figure 2:** Same as Fig.1 but for the differential rotational (d-) models.

ferential rotation, where they call the phenomenon "type III" wave form. If the coupling constant $\alpha_s = 0.25$, the coexistence area of two phases becomes small, and the effect on GWA by the transition becomes small (See Table 1), as well as uniformly rotating models.

The maximum amplitude $|h^{\rm TT}|_{\rm max}$ of the differential rotating models is about one digit larger than that of uniformly rotating (u-) models, which has been found in the Ref. [12, 23].

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