Vol 17 No 10, October 2008
1674-1056/2008/17(10)/3917-05

Chinese Physics B

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Effect of pressure grads on convection in inner core of type II supernova*

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(Received 31 January 2008; revised manuscript received 25 March 2008)

By adjusting the pressure grads in the stage of formation of the shock wave, a successful prompt explosion process has been numerically simulated through a progenitor model of 15Msolar, in which the effects of pressure grads on various convections, including the Rayleigh–Taloy (R-T) convection, the lepton driven convection and the negative entropy grads driven convection, in an inner core are analysed. The simulation results show that the increase of the pressure grads in the inner core region may cause a powerful convection, which causes energy transfer from the inner core to the shock wave rapidly and efficiently.

Keywords: supernova, convection, pressure grads
PACC: 9760B

1. Introduction

Supernova, i.e. the explosion of a massive star at the end of its lifetime, belongs to the most violent event in the universe. However, the event has not been explained satisfactorily because considerable uncertainties are involved. Colgate and John[1] first proposed the prompt explosion mechanism, but no explosion model has been developed successfully.[2,3] It is considered in the delayed explosion mechanism that since the prompt explosion mechanism cannot make shock wave energy dash out from the inner core due to not enough explosion energy, the stationary shock wave must be formed in the outer shell. Plentiful neutrinos, which are produced by proto-neutron stars, would heat the shock wave and revive the stationary shock wave. And it would burst through the stellar screen and form a successful supernova explosion. However many problems or questions about the neutrinos are still open. For example, the neutrino's productive mechanism and transport processes as well as its section cross of nuclear reaction need further determining urgently.[4] To solve the problems, Burrows *et al*[5] presented recently a new idea that acoustic energy, but not the neutrinos' energy, could clarify the stationary shock wave due to the fact that the acoustic energy can be absorbed completely by matter, which is more favourable for the successful explosion.

In principle, the multi-dimensional simulations are more helpful for achieving the successful explosion of supernova, but many of problems have been treated too simply up to now. For example, the entirely successful explosion model simplifies the treatment of the neutrinos transport processes.[5,6] In fact, there has been developed no absolutely successful explosion model as yet. In this paper, therefore, a successful prompt explosion model of supernova is attempted to be established by adjusting the pressure grads in the stage of shock wave forming. Based on the new model, the effects of pressure grads on convections in the inner core of supernova, including the R-T convection, the lepton driven convection and the negative entropy grads driven convection are discussed. Our previous work [7,16] shows that revised pressure grads have a little effect on the pressure and the energy of stellar but have a significant influence on explosion energy, which could increase the explosion energy remarkably. In the present paper we adopt a one-dimensional spherically symmetric program WLWY89[9] whose progenitor is 15Msolar and given by Woosley and Weaver[8] to simulate the supernova explosion, which has been introduced in detail in our previous work.[7,16]

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2. The revision of pressure grads and numerical simulation

In supernova explosion the electron capture plays an important role. Peng[17] shows that in the inner core of supernova, the mass density contracted by the iron core becomes so high that the electron capture can take place rapidly and the fraction of electrons decreases very fast. So the pressure in the core decreases rapidly and the pressure grads in the central region are changed. In our simulation the pressure P_j of mass layer j in the inner core is regard as adjustable through varying the parameter β, i.e. $P_j = P_{j+1} + \beta\Delta P_{j+1/2}$, with[7,16]

$$\beta = \begin{cases} 1, & t = 0, \\ 0.95, & 0 < t < 285.755\,\text{ms}, \\ 0.93, & 285.755\,\text{ms} < t < 291.953\,\text{ms}, \\ 1.45, & 291.953\,\text{ms} < t < 292.256\text{ms}, \\ 1, & t > 292.256\,\text{ms}. \end{cases}$$

In order to reduce the artificial adjustment, only the most key formation stage of shock wave is considered (in an about 3ms time range). In the stage the central density comes to maximum (about 2–3 times the density of nuclei). The shock wave takes place near by the point of sound speed . The instability of the inner core would increase with the pressure grads increasing, which would substantially increase the explosion energy and then increase the successful probability of simulating the supernova explosion. By debugging again and again, we find that, when β=1.45 in the stage of wave formation (i.e. the pressure grads increase 45% on the basis of the primary pressure grads) and fixing the pressure of collapse phase in a longer time correspondingly as well as the pressure of the rebound shock transfer phase, the explosion energy increases markedly. In our simulation the maximum values of the explosion energy can increase from 0.019 to 4.62foe. When shock waves come to the edge of iron core which is about 1.38Msolar in mass, the energy and the speed are 1.11foe and 2E9cm/s respectively. This may be considered as a successful result of supernova explosion. The total energy of the stellar system is not increased in our work, but where does so high explosion energy come from? Figure 1 shows a comparison between the kinetic energy $E_{\rm k}$ and the binding energy $E_{\rm b}$ in the inner core at the stage of shock wave formation, where the binding energy is the total energy including the gravity energy, the inner energy and so on. One can see that the maximum values of kinetic energy are about 9.78 and 10.37foe

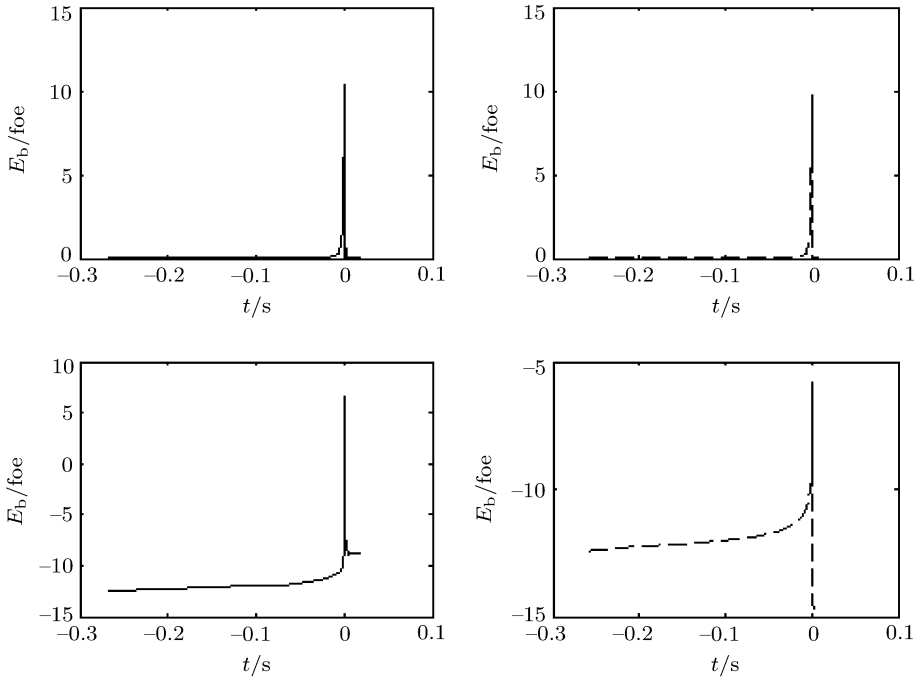


Fig.1. The kinetic energy $E_{\rm k}$ and binding energy $E_{\rm b}$ as a function of time t in the inner core before and after shock wave rebounding. T=0 is the time of rebounding; dashed line and solid line denote the energy distributions before and after revising the pressure grads respectively.

before and after revising pressure grads respectively. Obviously, the kinetic energy of inner core has little increase. According to viewpoint of Muller, the initial energy of shock wave is approximately equal to the kinetic energy of inner core,[10] that is to say, the initial energy of shock wave has a little increase due to the fact that pressure grad is not revised in the phase of collapse. While the binding energy has a remarkable change, the maximum value and minimum value are –5.83 and –14.5foe before revising the pressure grads and 6.67 and –8.77foe after revising the pressure grads respectively. According to Bruenn,[11] the maximum energy transferring from the inner core to the rebound shock wave can be expressed as $E_{\rm sh} = E_{\rm max} - E_{\rm min} - E_\nu$, where E_ν is the energy loss of neutrinos in the transformation process of rebound shock wave. The obtained shock wave energy would increase 78% at the expense of the loss energy of neutrinos, which may be enough to make a successful explosion. The initial speed would increase appreciably after revising the pressure grads, but the total energy which is provided for the shock wave in the process of forming and transforming rebound shock wave would increase markedly. We consider it as a result of the convection transformation energy in the process of providing energy, and the detailed discussion will be presented in the following section.

3. Convection in inner core region

3.1. R-T convection

R-T convection takes place in liquids of different densities under the action of gravity or inertia force. In supernova, the action of the gravity can be ignored. The enhancement factor, $G_{\rm RT}$, which is given by Chandrasekhar,[12] is determined by pressure grads as $G_{\rm RT} = \sqrt{Ak_n\left(-\frac{1}{\rho}\frac{{\rm d}p}{{\rm d}r}\right)}$, where $A = \frac{\rho_+ - \rho_-}{\rho_+ + \rho_-}$ is a twood number, ρ_+ and ρ_- denote the densities of up and down interfaces respectively, k_n is the disturbing wave number of interface and p is the pressure. The expression $\left(\frac{{\rm d}p}{{\rm d}r}\right)\left(\frac{{\rm d}\rho}{{\rm d}r}\right) < 0$ that may be further simplified into $\frac{\partial\rho}{\partial p} < 0$ usually serves as a criterion of R-T convection occurring. Figure 2 shows the dimensionless $\partial\rho/\partial p$ as a function of mass and radius for various times in the phases of shock wave formation and transmission. One can find that the regions for $\frac{\partial\rho}{\partial P} < 0$ exist only in the inner core (shock formation in 0.78Msolar), showing that no R-T convection occurs from the region. The region of instability would diffuse with shock wave. In particular, in the middle of proto-neutron stars (near the region of 0.4Msolar), the region where the condition of R-T convection occurring is met is largest. Furthermore, in the stellar interior there also exist the fraction instability regions which may be related to the hypo-shock wave formation.

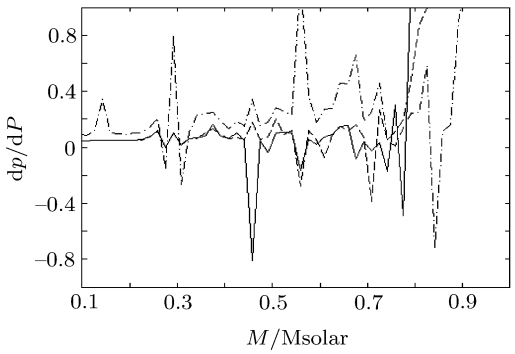


Fig.2. $\partial\rho/\partial p$ as a function of mass or radius for various times, with solid line, dash line and dot line denoting the times for the central density to achieve its maximum , and for the shock wave to achieve 0.8Msolar and 0.9Msolar separately.

3.2. Convection driven by lepton grads

In the process of collapse of supernova, other instabilities result from negative lepton grads which include electrons and neutrinos. Generally speaking, the electron abundance ($Y_{\rm e}$) is far more than the neutrino abundance (Y_v), then the lepton driven convection is determined by electron abundance only. It is extremely important to study the region where $Y_{\rm e}$ grads is negative for convection. $Y_{\rm e}$ increases gradually from the centre to the edge in presupernova, and the entire $Y_{\rm e}$ grads are positive. The weak interaction process leads the electron abundance to decrease rapidly, which in turn affects $Y_{\rm e}$ grads. About twenty years ago, Epstein pointed out that the instability in supernova could occur due to the decreasing of $Y_{\rm e}$ grads.[13] Later, Wilson and Mayle [14] also proposed that the "neutron figure convection" was also attributed to the negative $Y_{\rm e}$ grads essentially. Figure 3 shows the lepton distribution as a function of mass or radius for various times. Both of the processes of shock wave rebound and transfer from the centre to the head of wave have the negative $Y_{\rm e}$ grads. This shows that the

entire core transfers energy into the shock wave due to the convection driven by lepton with a small Y_e grads. We find that the convection of Y_v is also evident in wave plane although Y_v is far less than Y_e. Compared with R-T convection where the distribution region is narrow and changes with time rapidly, the convection driven by Lepton grads almost distributes in the whole inner core and remains stable for a longer time.

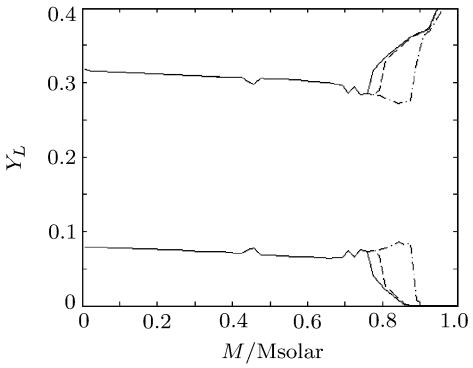


Fig.3. Lepton distribution as a function of mass or radius for various times. The upper and lower curves represent the distributions of Y_e and Y_v respectively, and the other remark of the figure is the same as that in Fig.2.

3.3. Convection driven by negative entropy grads

Low entropy is the prominent characteristic due to the neutrinos loss in the process of collapse of supernova.[15] The closer to the centre, the lower entropy, and the entire entropy grads are positive radially. In the stage of rebound of shock wave, the maximum entropy takes place at the head of wave due to the steep rise of temperature and in turn gives rise to an increase in entropy. The negative entropy grads are very evident in the region of producing and transferring shock wave, and then the convection near the head of wave is determined by the driven negative entropy. Figure 4 shows the curves of entropy as a function of mass and as a function of radius for various times, separately. One can find that the position of rebound shock wave still keeps up with the high entropy in a shorter time range after the shock rebound. Then there appears a region of a relatively stable negative entropy grad near the position of 0.78Msolar. Moreover, there also exist some regions with sporadic negative entropy grads in 0.25–0.7Msolar, which are near to those of hypo-shock wave. We should point out that the energy transfers to shock wave stepwise, where the hypo-shock wave serves as a propagator. The powerful hypo-shock wave would increase shock wave energy markedly.

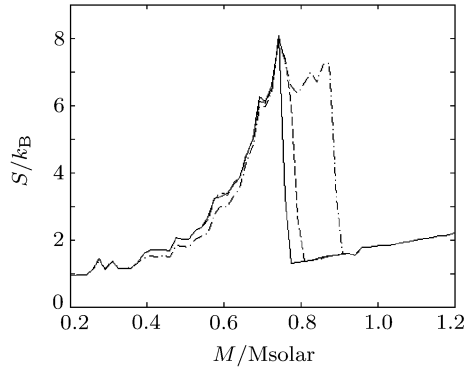


Fig.4. Entropy as a function of mass or radius for various times. The other remark of the figure is the same as that in Fig.2.

Our simulation shows that the presence of above several convections in the inner core is very evident and exact. We think that the convections in the inner core may include some other convections in nature, such as the Ledoux convection which exists in the regions of both negative entropy grads and negative Y_e grads. Therefore, what is observed is the resulting combination of various convections. Near the head of wave, various convections including the R-T convection, the lepton driven convection, the negative entropy driven convection and so forth are present simultaneously. The hypo-shock wave in the inner core transfers the energy to the position where the shock wave occurs, that is, the hypo-shock wave supplements the shock wave with energy. Therefore, the hypo-shock wave is also important.

4. Conclusion

Our wok shows that the instability occurs in the supernova explosion and the convection may be one of the explosion mechanisms. In our simulation the instability of inner core is achieved by man-made revising pressure grads for researching into the effect of convection on supernova explosion. The physical essence of the strong convection in the inner core will be investigated in our future work.

Acknowledgement

The authors would like to thank Y.Z. Wang, S.C. Zhang, Z.H. Xie and W.Z. Wang for providing the original program Wlyw89 for simulating the SN explosion.

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