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Re-research on the size of proto-neutron star in core-collapse supernova*

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The electron capture timescale may be shorter than hydrodynamic timescale in inner iron core of core-collapse supernova according to a recent new idea. Based on the new idea, this paper carries out a numerical simulation on supernova explosion for the progenitor model $Ws15M_{\odot}$. The numerical result shows that the size of proto-neutron star has a significant change (decrease about 20%), which may affects the propagation of the shock wave and the final explosion energy.

Keywords: supernova explosion, proto-neutron star, shock wave
PACC: 9760B, 2340

1. Introduction

A massive star ($M > 8M_{\odot}$) often ends its life by supernova (SN) explosion, and approximately 10^{53} erg of energy are released most in the form of neutrinos. For a presupernova model with mass of $15\,M_{\odot}$, the mass of the iron core is about $1.37\,M_{\odot}$ and the envelope consists of Si, C, O, He and H. The electron degenerate pressure prevents the inexorable contraction induced by the star's self-gravity. The composition of presupernova is altered by weak interactions (mainly electron capture and beta decay). As the core of the presupernova exceeds the appropriate Chandrasekhar mass, the electron degenerate pressure can not prevent the star from contraction. In the early stage of collapse, electron capture plays an essential role. It not only reduces the number of leptons per baryon, but also carries huge energy and entropy away from the core in the form of neutrinos and cools the core (Thus, low entropy is a character of the collapse.). Those effects conspire to accelerate the collapse.[1−3] In the inner regions of iron core, this collapse is subsonic and homologous, while the outer region is supersonic. The largest velocity of the boundary between them is about $0.125c$–$0.25c$ (c is the velocity of light). The densities in the centre increase dramatically with the collapse. As the densities of the centre reach the maximum (2–3 times of nuclear density), the core cannot be contacted and the falling outer core collides stiffen inner core and produces the bounce shock. However, detailed numerical model indicates that the shock is not able to rush out of the iron core because too much energy will be lost in the photodisintegration of iron nuclei to free nucleons (124.4 MeV for $\gamma+{}^{56}\mathrm{Fe}\rightarrow 13\,\mathrm{He}+4\mathrm{n}$, 28.3 MeV for $\gamma+{}^{4}\mathrm{He}\rightarrow 2\mathrm{n}+2\mathrm{p}$. So for each nucleus photodisintegration it needs energy of 8.8 MeV). Shock stalls in the envelopes. If the intense neutrinos flux from the proto-neutron star (PNS)[4] heats the stalled shock and drives off the envelopes,[5] the SN explosion comes true. Unfortunately, although theoretical research and numerical simulation have got great progress since collapse–bounce mechanism is proposed by Clogate and White[6] (various physical factors such as convection, rotation, magnetic fields and general relativistic effects), updated physics including updated nuclear information (such as nuclear equation of state and nuclear parameters) improved presupernova models,[7] neutrino physics (such as neutrino energy transfer by multigroup Boltzmann simulations, weak interaction in sub-nuclear region, especially neutrino interaction with various kinds of particles and 1,2,3-dimensional simulations are all considered), the elaborate calculations indicate that the success of SN explosion is difficult.[8] So some new mechanisms were proposed

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in recent year,[9−11] which provide some new possible routes to resolve the puzzle of SN explosion. In this paper, we investigate the collapse of the core-collapse supernova according to the new proposal proposed by Peng.[9] Progenitor model in our work is Ws15M$_\odot$.[12] The numerical simulations are performed by using a modified version of program Wlyw89, in which the equation of state is given by Wang *et al.*[13] The model is divided into 96 layers averagely and its boundary is at 1.6 M$_\odot$ in the numerical simulations.

2. Electron capture timescale and electron degenerate pressure

In the usual SN simulations the difference between electron capture timescale, $t_{\rm ec}$, and hydrodynamic timescale, $t_{\rm dyn}$, is ignored because usually the $t_{\rm ec}$ is much longer than $t_{\rm dyn}$ when the density is not high enough. But at the last stage of collapse, this situation may reverse. For the sake of the reversion situation in the late collapse, Peng argued that as the iron core contracts, the densities of the central region of the core will get so high that the electron capture will become very rapid, even the electron capture timescales $t_{\rm ec}$ will be shorter than hydrodynamic timescale $t_{\rm dyn}$, more electrons can be captured by heavy nuclei and protons, which will induce the decrease of electron degenerate pressure, and the total pressure is associated (electron degenerate pressure is mainly for the total pressure at collapse stage). This effect triggers the inner core accelerating collapse with a larger acceleration than that in fiducial case. Simultaneously, the outer core collapses almost in the conventional way. The detailed calculations of $t_{\rm ec}$ and $t_{\rm dyn}$ can be found in Refs.[14–16]. We find that, at the beginning, the mass densities of the outer iron core are comparatively low and only the central core satisfies the condition $t_{\rm ec} < t_{\rm dyn}$. Nevertheless, more and more shells (from the inner to outer) satisfy the condition $t_{\rm ec} < t_{\rm dyn}$ with time. For Ws15M$_\odot$ model, Fig.1 shows the comparison of two timescale after 0.1025 s from simulation and Fig.2 shows the shell number satisfying the condition $t_{\rm ec} < t_{\rm dyn}$. One can find from Figs.1 and 2 that only the centre region satisfies the condition ($t_{\rm ec} < t_{\rm dyn}$) at 0.112s after simulation and the shell extent to 65 (total 96, position is about 1.0 M$_\odot$). From the analysis we find that the difference is obvious.

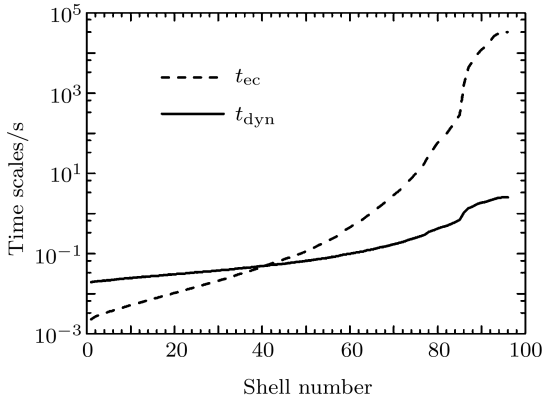


Fig.1. The comparison of electron capture timescale and hydrodynamic timescale after 0.1025 s from simulation.

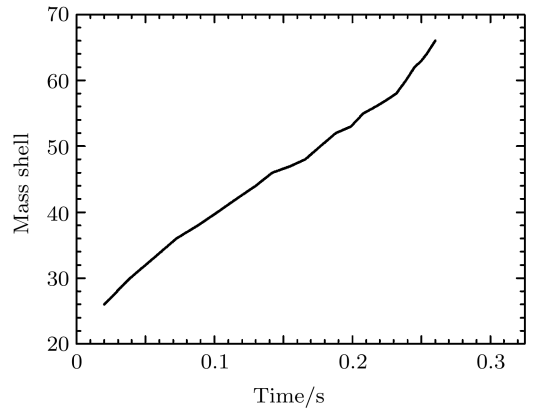


Fig.2. The number of the mass shell in which $t_{\rm ec} < t_{\rm dyn}$ is valid at different collapsing moments.

According to Peng's new criterion, we make an estimate to a time step ΔT in numerical simulation with $t_{\rm ec} < t_{\rm dyn}$. The conventional time step is ΔT, the electron capture equivalent time step is $\Delta T_{\rm ec} = \dfrac{t_{\rm ec}}{t_{\rm dyn}}\Delta T$, and the residual time in a conventional time step is $\Delta T' = \Delta T - \Delta T_{\rm ec}$. Namely, the capture time comparatively prolongs $\Delta T'$ in which the protons and heavy nuclei can capture more electrons, which must cause the decrease of degenerate pressure of electron. The capture rates in unit volume, $S_{\rm e}$, is $-{\rm d}n_{\rm e}/{\rm d}t$,[13] where $n_{\rm e}$ is the number density of electrons. Further, we can get

$$ {\rm d}n_{\rm e} = -S_{\rm e}{\rm d}t. \tag{1} $$

Since the time step ΔT is so short in our calculation in which $S_{\rm e}$ can be regarded as a constant in each time step. The number density of electron can be written as

$$ n_{\rm e} = \frac{\rho}{m_{\rm N}} Y_{\rm e}, \tag{2} $$

where ρ, $m_{\rm N}$, $Y_{\rm e}$ are the mass density, the nucleon mass and the number of proton per baryon respec-

tively. At density over $10^7\,\mathrm{g\cdot cm^{-3}}$, the electrons are relativistic and degenerate, so the pressure of electron gas has following form[17]

$$P_\mathrm{e} = \frac{c}{4}\left(\frac{3h^3}{8\pi}\right)^{1/3} n_\mathrm{e}^{4/3} = \frac{c}{4}\left(\frac{3h^3}{8\pi}\right)^{1/3}\left(\frac{\rho}{m_\mathrm{N}}Y_\mathrm{e}\right)^{4/3}, \quad (3)$$

here h is the Planck constant, we approximate that the change of Y_e can be neglected in such a short time step. So we get $\mathrm{d}P_\mathrm{e} \sim \frac{4}{3}\mathrm{d}Y_\mathrm{e}$ from Eq.(3) and $\Delta T \sim \mathrm{d}n_\mathrm{e} \sim \frac{3}{4}\mathrm{d}P_\mathrm{e}$ from Eqs.(1), (2) and (3), $\mathrm{d}Y_\mathrm{e} = \dot{Y}_\mathrm{e}\mathrm{d}t$. In our calculation, the iron core is composed of four particles (free neutrons, free protons, α particles and average heavy nuclei).[13] Since only free protons and heavy nuclei can capture electrons, the total electron capture rates are obtained by $\lambda_\mathrm{p} + \lambda_\mathrm{H}$, where λ_p and λ_H are the capture rates of the protons and the average heavy nuclei respectively.

$$\begin{aligned}\dot{Y}_\mathrm{e} &= \dot{Y}_\mathrm{eH} + \dot{Y}_\mathrm{ep} \\ &= -\chi_\mathrm{H} Y_\mathrm{e}\rho N_\mathrm{A} x c\hat{\sigma}_0 \iint \frac{3}{\mu_\mathrm{e}^3}\left(\frac{\varepsilon_\nu}{m_\mathrm{e}c^2}\right)^2 \varepsilon_\mathrm{e}^2 \mathrm{d}\varepsilon_\mathrm{e}\frac{3m_\mathrm{p}}{k_\mathrm{f}^2}\mathrm{d}\varepsilon_\mathrm{p} \\ &\quad -\chi_\mathrm{p}\frac{8\pi c\hat{\sigma}_0}{(hc)^3}\int\left(\frac{\varepsilon_\nu}{m_\mathrm{e}c^2}\right)^2 \varepsilon_\mathrm{e}^2\mathrm{d}\varepsilon_\mathrm{e}, \end{aligned} \quad (4)$$

where χ_H, χ_p are the fraction of average heavy nuclei and free proton respectively. N_A is the Avogadro constant, $x = Z/A$, $\hat{\sigma}_0 = 1.18\times10^{-44}\,\mathrm{cm^2}$, c is the velocity of light, μ_e is the chemical potential of electron, ε_ν, ε_p, ε_e are the energy of neutrino, proton and electron respectively, m_e, m_p are the mass of electron and proton respectively, k_f is the Fermi momentum.

The total pressure of iron core $P = P_\mathrm{e} + P_\mathrm{h} + P_\mathrm{y} + P_\nu + P_\gamma$, where P_h is the pressure of nuclei, P_y, the gas pressure of neutrons, protons, α particles and average heavy nuclei. P_ν and P_γ are the pressure of neutrinos and photons respectively. Accordingly, from the difference of t_ec and t_dyn we can derive the change of pressure of electron, as well as the change of total pressure, which trigger the accelerating collapse when $t_\mathrm{ec} < t_\mathrm{dyn}$. The decrease of Y_e also can be derived from Y_e to $Y_\mathrm{e} + \dot{Y}_\mathrm{e}\Delta T'$, which derives that the total Y_e will be smaller than before. The decrease of electron pressure results in the accelerating of inner core. The time in which the central density changes from $10^{12}\mathrm{g\cdot cm^{-3}}$ to the maximum reduces from 6.51 ms to 5.53ms because of the accelerating.

3. Results and analysis

According to the above discussion, we make the simulations of the collapse on presupernova model $\mathrm{Ws15M_\odot}$ and make a comparison with the fiducial case. Due to too many parameters in the simulations, here we just give some key parameters at the moment of beginning bounce, in which the centre gets its maximal density. Figure 3 shows the electron fraction Y_e and neutrino fraction Y_ν with the enclosed mass. Due

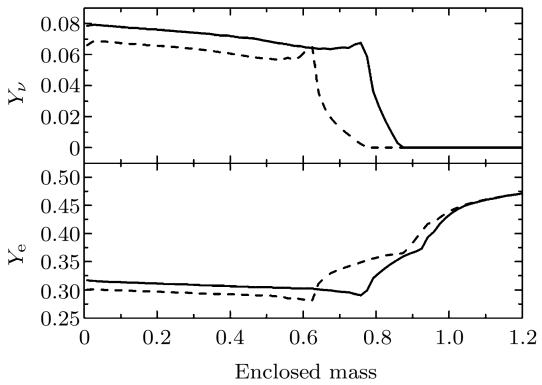


Fig.3. The neutrino fraction and electron fraction as functions of the enclosed mass at the beginning of the bounce for $\mathrm{Ws15M_\odot}$ model. The solid line and the doted line are corresponding application of the conventional criterion and the new criterion respectively.

to application of the new criterion, which makes that more electrons are captured during the collapse process, one can find from Fig.3 that both Y_e and Y_ν have a remarkable reduction and that the trapping position of lepton fraction $Y_\mathrm{L}(Y_\mathrm{L} = Y_\mathrm{e} + Y_\nu)$ is more close to the centre. Figure 4 shows the distribution of entropy per baryon and the velocity of shock wave with the enclosed mass. The position corresponding to the

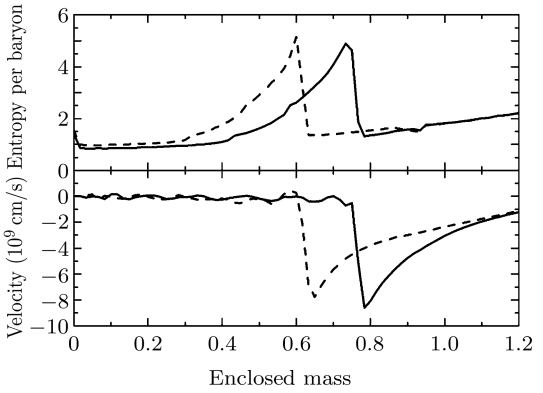


Fig.4. The entropy and velocity as functions of the enclosed mass at the beginning of the bounce for $\mathrm{Ws15M_\odot}$ model. Notes are similar to Fig.3.

maximal entropy and the maximal velocity are decreased and almost consistent with the trapping position of lepton fraction. The reason is that the edge of PNS appear at the maximal entropy and the velocity,[13] and the size of PNS is proportional to the square of the mean trapped lepton fraction.[18] All these indicate that the size of PNS decreases. From Figs.3 and 4 we find that the size of PNS changes from $0.77\,M_\odot$ to $0.62\,M_\odot$ (reduces about 20%) with application of the new criterion.

In general, a remarkable reduction of the radius of the PNS means that the outer layers of the core become thicker. If the outer layer of iron is fully photodisintegrated (classical theory), the shock wave must consume more energy in the photodisintegration and the success of SN explosion becomes more difficult. But according to Peng's idea,[9] the success of SN explosion does not depend on the full photodisintegration. The composition and the position of the outer part of iron core are altered. On one hand, the degree of the neutralization of the nuclei in outer part of iron core decreases because outer core collapses almost in the conventional way and the collapse time becomes shorter. On other hand, one can find from Fig.5 that the radii of the outer part increase and the densities decrease.

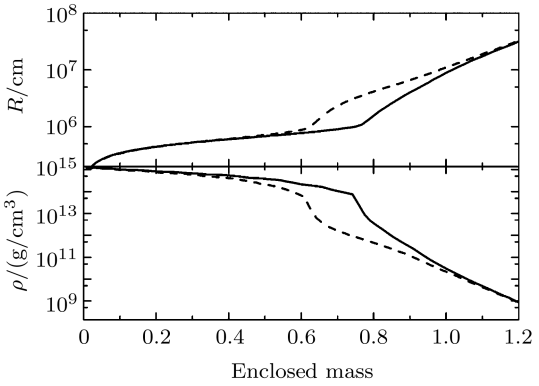


Fig.5. The radii and density as functions of the enclosed mass at the beginning of the bounce for a Ws15$M_\odot$ model. Notes are similar to Fig.3.

The collapsing core is divided into two parts, the rapid collapsed inner core and free-fall collapsed outer core. Because the mass of the inner collapsed core is obviously smaller than the prior case, shock can rush out of the inner core. Of course, if the temperature of the outgoing shock wave is larger than 10^{11} K, iron nuclei will be photodisintegrated. But temperature of shock will decrease quickly below 10^{11} K at $1.0\,M_\odot$ (Fig.6), which blows the photodisintegration energy of iron nuclei, or only partial photodisintegration.

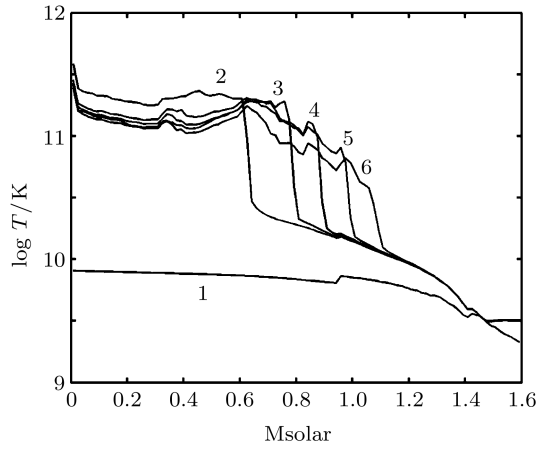


Fig.6. The temperature of SN as functions of the enclosed mass. 1: At the beginning of collapsing. 2: The density of the central core arrives the maximum. 3∼6: Shock wave arrives, the positions are $0.8\,M_\odot$, $0.9\,M_\odot$, $1.0\,M_\odot$, $1.1\,M_\odot$ respectively.

In a very short time interval (less than 10^{-7} s), a very strong neutrino flux will be produced and transferred out to the collapsed core.[3] The averaged energy of neutrinos is about 10 MeV. The neutrino flux will almost catch up with the outgoing rebound shock wave. Both of the radiation field of the shock wave and the neutrino flux march outwards. The disintegration and the neutrino induced disintegration process of iron nuclei may not happen. The total energy $E_{\rm tot} = aT^4(4\pi/3)R^3$, where a is the radiation constant. But the iron nuclei are coherently scattered by the neutrino with the average energy ~ 1 MeV. The cross section of the coherent scatter by the neutrino is about $\sigma \sim 1.6\times10^{-44}(\sin\theta_{\rm W})^4A^2(E_\nu/{\rm MeV})^2{\rm cm}^2$, where $\theta_{\rm W}$ is the Weinberg angle, A is the atomic weight of the nuclei. The SN explosion may be successful just due to the coherent scatter of iron nuclei with neutrinos and also due to the radiation pressure.

The results we get are similar to what Hix *et al* and Langanke *et al* obtained.[5,19] They investigated the effect of improved electron capture rates on the heavier nuclei, especially on the nuclei with $N > 40$, which is regarded blocking by FFN, to the SN explosion. Due to applying different equation of state and presupernova models in our simulations, the size of PNS we obtain is larger than that Hix *et al* and Langanke *et al* obtained. If both the new criterion and

the improved electron capture rates are considered simultaneously, the effect on size of PNS will increase. Furthermore, in two or three dimensional cases the effect could be further increase because the collapse timescale in the axial direction is comparatively short. The effect of electron screening should also be considered in our future work.

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References

[1] Bethe H A, Brown G E, Applegate J and Lattimer J M 1979 *Nucl. Phys.* A **324** 487
[2] Langanke K and Martinez-Pinedo G 1999 *Phys. Lett.* B **453** 187
[3] Liu M Q, Zhang J and Luo Z Q 2006 *Acta Phys. Sin.* **55** 3198 (in Chinese)
[4] Dai Z G, Peng Q H and Lu T 1995 *ApJ* **440** 815
[5] Hix W R, Messer O E, Mezzacappa A, Liebendörfer M, Sampaio J, Langanke K, Dean D J and Martínez-Pinedo G 2003 *Phys. Rev. Lett.* **91** 201102
[6] Colgate S A and White R H 1966 *ApJ* **143** 626
[7] Heger A and Woosley S E 2001 *ApJ* **560** 307
[8] Buras B, Rampp M, Janka H T and Kifonidis K 2003 *Phys. Rev. Lett.* **90** 241101
[9] Peng Q H 2004 *Nuclear Physics* A **738** 515
[10] Peng Q H 2004 *Americal Astronemical Society Mecting 205* **306** 1463
[11] Burrows A, Livne E, Dessart L, Ott C D and Murphy J 2006 *ApJ* **640** 828
[12] Woosley S E and Weaver T A 1995 *ApJ* Suppl. **101** 181
[13] Wang Y R, Zhang S C, Xie Z H and Wang W Z 2003 *Supernova Mechanism and Numerical Simulation* (Zhengzhou: He-Nan Science Press) (in Chinese)
[14] Luo Z Q, Liu M Q, Peng H Q and Xie Z H 2006 *ChJAA.* **6** 455
[15] Luo Z Q, Liu M Q, Lin L B, Peng H Q and Lin L M 2005 *Chin. Phys.* **14** 1272
[16] Liu M Q, Luo Z Q and Zhang J 2007 *Chin. Phys.* **16** 3146
[17] Lan K R 1983 *Astrophysical Formulas* (Shanghai: Shang-Hai Science and Technology Press (in Chinese)
[18] Yahil A 1983 *ApJ* **265** 1047
[19] Langanke K, Martinez-Pinedo G, Sampaio J M, Dean D J, Hix W R, Messer O E, Mezzacappa A, Liebendörfer M, Janka H Th and Rampp M 2003 *Phys. Rev. Lett.* **90** 241102