Death of Massive Stars: Supernovae and Gamma-Ray Bursts
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Neutrino-driven supernova explosions powered by nuclear reactions

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Abstract. We have investigated the revival of a shock wave by nuclear burning reactions at the central region of core-collapse supernovae. For this purpose, we performed hydrodynamic simulations of core collapse and bounce for 15 $M_\odot$ progenitor model, using ZEUS-MP code in axi-symmetric coordinates. Our numerical code is equipped with a simple nuclear reaction network including 13 α nuclei form ^{4}He to ^{56}Ni, and accounting for energy feedback from nuclear reactions as well as neutrino heating and cooling. We found that the energy released by nuclear reactions is significantly helpful in accelerating shock waves and is able to produce energetic explosion even if the input neutrino luminosity is low.

Keywords. hydrodynamics, neutrinos, nuclear reactions, nucleosynthesis, abundances, shock waves, supernovae: general

1. Introduction

In this work we argue that the energy released by nuclear reactions may be able to realize the revival of a shock wave which stalls inside the iron core of a supernova progenitor because of endothermic photodisintegration reaction. The exact mechanism of the explosion and the crucial ingredients are still controversial, and neutrino-driven explosion model is one of the mechanisms suggested for core-collapse supernova explosion (Scheck *et al.* 2008; Marek & Janka 2009). Moreover, nuclear energy is a possible propellant of shock into energetic supernova explosions. We present the numerical simulations of core-collapse supernovae by means of multi-dimensional hydrodynamic code including a simple nuclear reaction network including 13 alpha nuclei.

2. Numerical Scheme and Results

A 15 $M_\odot$ star (Limongi & Chieffi 2006) is employed for the progenitor star. Details regarding numerical codes and results for the other models are summarized in our forthcoming paper (Nakamura *et al.* in preparation).

In Figure 1 we present a snapshot of the distributions of entropy and some representative elements for neutrino luminosity $L_{\nu,0} = 3.0 \times 10^{52}$ erg s^{-1} which decays exponentially in a time scale $t_d = 1.1$ s. We can see that oxygen is completely burned out and heavier nuclei like silicon are produced at a weak shock in accreting gas, followed by a strong shock wave where a fraction of silicon is converted into nickel. Soon the strong shock

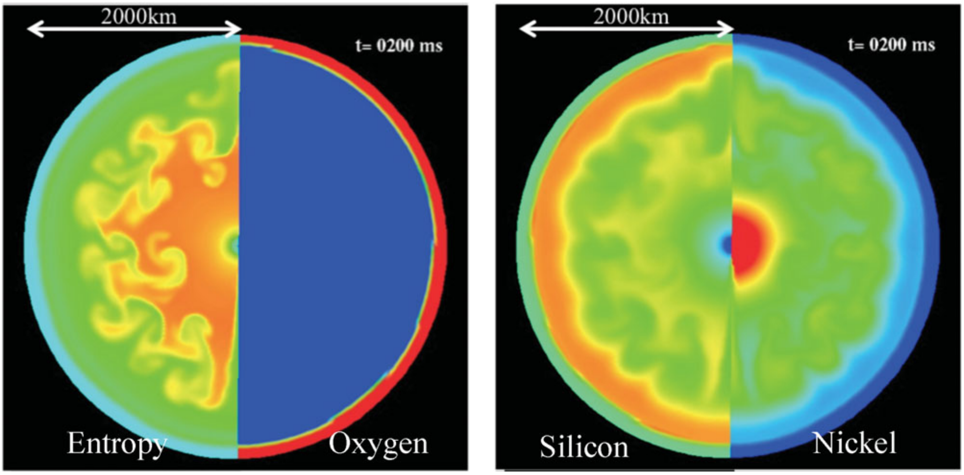

Figure 1. A snapshot of the distributions of entropy and some representative elements at $t_{pb} = 200$ ms within the radius $r = 2000$ km. Shown is the result from 2-dimensional simulation for LC15 model with $L_{\nu,0} = 3.0 \times 10^{52}$ erg s^{-1} and $t_d = 1.1$ s.

wave catches up with the weak shock front and at this phase the energy deposition rate through nuclear reactions shows a rapid rise and heats up the region behind the shock front, resulting in the shock acceleration and increasing explosion energy. The entropy profile behind the strong shock shows hydrodynamic instability which well mixes materials behind the shock front. In general such kinds of hydrodynamic instabilities make accreting materials remain at so-called "gain region" and help neutrino heating become effective. Compared to spherical explosions, we confirmed that the effects of spatial dimensions enhance the efficiency of neutrino heating and 2-dimensional models explode more easily in terms of shock velocity and also the minimum neutrino luminosity for explosion. For example, with a fixed t_d of 1.1 s and without nuclear energy, spherical explosions need initial neutrino luminosity more than 2.5×10^{52} erg s^{-1}. On the other hand, for the 2-dimensional explosion case, the minimum neutrino luminosity is reduced to 2.2×10^{52} erg s^{-1}. The effect of nuclear reactions becomes outstanding when the input neutrino luminosity is low. Taking the case of $L_{\nu,0} = 2.4 \times 10^{52}$ erg s^{-1} and $t_d = 3.0$ s as an example, we obtained final explosion energy of 8.1×10^{50} erg with the aid of nuclear reactions. This parameter set holds itself explosive even if a hydrodynamic energy equation does not include the term of the energy released via nuclear reactions. In the case without nuclear reactions, however, the final explosion energy is 5.9×10^{50} erg, more than 25 % less than the case with nuclear reactions. This shortage corresponds to the net energy released via nuclear reactions.

We conclude that nuclear reactions obviously contribute to shock acceleration and bulking up of explosion energy of core-collapse supernovae. In order to make this process effective a shock front needs to break out of the iron core and reach the oxygen-rich layer, which should be driven by neutrino heating or other energy sources.

References

Limongi, M. & Chieffi, A. 2006, *ApJ*, 647, 483
Marek, A. & Janka, H.-T. 2009, *ApJ*, 694, 664
Nakamura, K., Takiwaki, T., Kotake, K., & Nishimura, N. in preparation
Scheck, L., Janka, H.-T., Foglizzo, T., & Kifonidis, K. 2008, *A&A*, 477, 931