Death of Massive Stars: Supernovae and Gamma-Ray Bursts
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Nucleosynthesis in neutrino-driven, aspherical Population III supernovae

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Abstract. We investigate explosive nucleosynthesis during neutrino-driven, aspherical supernova (SN) explosion aided by standing accretion shock instability (SASI), based on two-dimensional hydrodynamic simulations of the explosion of 11, 15, 20, 25, 30 and $40 M_{\odot}$ stars with zero metallicity. The magnitude and asymmetry of the explosion energy are estimated with simulations, for a given set of neutrino luminosities and temperatures, not as in the previous study in which the explosion is manually and spherically initiated by means of a thermal bomb or a piston and also some artificial mixing procedures are applied for the estimate of abundances of the SN ejecta.

By post-processing calculations with a large nuclear reaction network, we have evaluated abundances and masses of ejecta from the aspherical SNe. We find that matter mixing induced via SASI is important for the abundant production of nuclei with atomic number $\geqslant 21$, in particular Sc, which is underproduced in the spherical models without artificial mixing. We also find that the IMF-averaged abundances are similar to those observed in extremely metal poor stars. However, observed [K/Fe] cannot be reproduced with our aspherical SN models.

Keywords. Supernovae: general, nuclear reactions, nucleosynthesis, abundances.

1. Introduction

Recent high resolution spectroscopy of metal poor stars (MPSs) showed that the scatters of abundance ratio of the stars around averaged abundance-ratios are small (e.g. Cayrel *et al.* (2004)). The observed ratios are well reproduced by IMF-averaged ejecta of supernovae (SNe) of Population (Pop) III stars, as in Tominaga *et al.* (2007) and Heger & Woosley (2010). The spherical models of Tominaga *et al.* (2007) and Heger & Woosley (2010) however require artificial matter mixing of SN ejecta to reproduce the observed abundances. Abundances of nuclei with $Z \geqslant 21$ in SN ejecta with aspherical model of Joggerst *et al.* (2009) and Joggerst *et al.* (2010), in which the explosion is spherically triggered but matter mixing through Rayleigh-Taylor (RT) instabilities is taken into account during later explosion phase, are underproduced compared with the observed abundances. Standing accretion shock instability (SASI) is a reliable candidate to initiate bipolar oscillations of a stalled shock. Successful explosion could occur via efficient neutrino heating induced via the bipolar oscillations (e.g. Marek & Janka(2009) and Suwa *et al.*(2010)). In addition to the importance of SASI to the explosion, material mixing due to SASI may change abundances and masses of the SN ejecta.

In the present work, we examine explosive nucleosynthesis in neutrino-driven, aspherical SNe of Pop III stars aided by SASI, based on two-dimensional (2D) hydrodynamic simulations of the SN explosion of the stars. In §2 we briefly describe a numerical code

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for hydrodynamic calculation of SN, initial setup, and properties of the explosion. In §3, we present abundances of the SN ejecta. Finally we will summarize our results in §4.

2. Hydrodynamic simulations of supernovae

For 2D hydrodynamic simulations of neutrino-driven SNe, we employ a numerical code, which is based on the ZEUS-2D code, as in Ohnishi *et al.* (2006) and Fujimoto *et al.* (2011). We assume that the fluid is axisymmetric and that neutrinos are isotropically emitted from the neutrino spheres with given luminosities and with the Fermi-Dirac distribution of given temperatures. Initial conditions for the hydrodynamic simulations are similarly arranged as in Fujimoto *et al.* (2011). The central region inside 50 km in radius is excised to follow a long-term postbounce evolution. We impose velocity perturbations to the unperturbed radial velocity in a dipolar manner, and follow the postbounce evolution.

We have performed the simulations for six non-rotating progenitors, whose main-sequence masses, $M_{\rm ms}$, are 11, 15, 20, 25, 30 and 40 $M_\odot$ with zero metallicity in Heger & Woosley (2010), for $1-2$s after the core bounce, when a shock front has reached to a layer with $r = 10,000\,$km in almost all directions. We consider models with neutrino temperatures, T_{ν_e}, $T_{\bar{\nu}_e}$, and T_{ν_x} as 4, 5, and 10 MeV, respectively, as in Ohnishi *et al.* (2006) and Fujimoto *et al.* (2011). We take the input neutrino luminosities from $L_{\nu_e,\rm min}$ to $L_{\nu_e,\rm max}$ for a given $M_{\rm ms}$, because the revival of the stalled bounce shock occurs only for models with $L_{\nu_e} \geqslant L_{\nu_e,\rm min}$ and also because for models with $L_{\nu_e} > L_{\nu_e,\rm max}$, the star explodes too early for the SASI to grow. Here $L_{\nu_e,\rm min}$ are 1.2, 2.0, 4.3, 7.0, 6.0, and 21.0 in units of $10^{52}\,{\rm erg\,s^{-1}}$ for $M_{\rm ms}/M_\odot = 11$, 15, 20, 25, 30, and 40, respectively, $L_{\nu_e,\rm max}$ are 6.0, 8.0, 8.0, 20.0, 10.0, and 28.0 in units of $10^{52}\,{\rm erg\,s^{-1}}$, respectively.

We note that abundances of SN ejecta are shown to depend not directly on L_ν and T_ν, but on the explosion energy and the mass of the proto-neutron star, as shown in Fujimoto *et al.* (2011). It should be emphasized that magnitude and asymmetry of the explosion energy are evaluated for the simulations. Moreover, we stress that estimated masses of the central remnant are less than $2.5 M_\odot$, which is lighter than the maximum, baryonic mass of a neutron star ($2.61 M_\odot$ for Shen EOS in O'Connor & Ott (2011)), for all models, and the onset of the explosion is earlier than the time for black hole formation estimated by O'Connor & Ott (2011), in particular for models with explosion energies $>10^{52}\,$erg.

3. Abundances of supernova ejecta

Next we calculate abundances and masses of the SN ejecta in a same manner as in Fujimoto *et al.* (2011). Ejecta that is located on the central part of the star ($\leqslant 10,000\,$km) before the core collapse has high enough maximum temperatures for elements heavier than C to burn explosively. We therefore follow abundance evolution of the ejecta from the central region using a nuclear reaction network, which includes 463 nuclides from neutron, proton to Kr, while the abundances of ejecta from outside the region are set to be those before the core collapse in Heger & Woosley (2010).

Figure 1 shows masses of Fe, $M({\rm Fe})$ as a function of $E_{\rm exp}$ in the SN ejecta for all models (left panel) and [Mg/Fe] as a function of $E_{\rm exp}$ for all models (right panel), where [A/B] is defined as $\log\left[(X({\rm A})/X({\rm B}))\,/\,(X({\rm A})_\odot/X({\rm B})_\odot)\right]$ with mass fractions of $X({\rm A})$ and $X({\rm B})$ for nuclei A and B. We find that $M({\rm Fe})$ roughly correlates with $E_{\rm exp}$. For $M_{\rm ms} = 11 M_\odot$ ($15 M_\odot$), $M({\rm Fe})$ ranges from $5\times10^{-5} M_\odot$ ($2\times10^{-3} M_\odot$) to $3\times10^{-2} M_\odot$ ($1\times10^{-1} M_\odot$), while for a given $M_{\rm ms}$ larger than $20 M_\odot$, $M({\rm Fe})$ are comparable because

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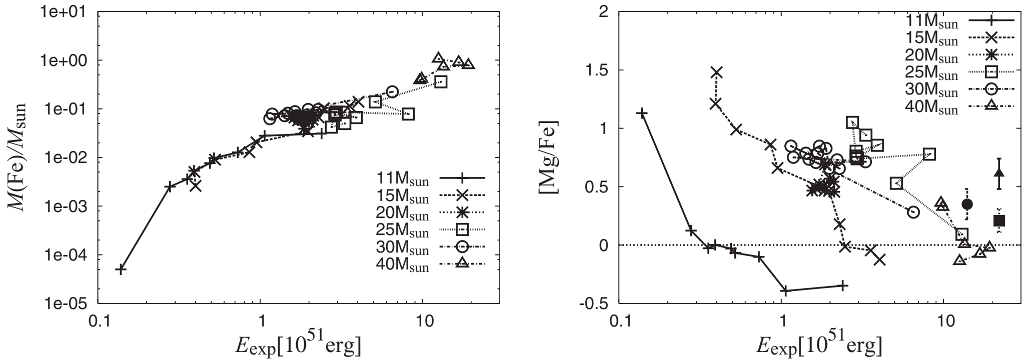

Figure 1. left: masses of Fe as a function of $E_{\rm exp}$ for all models. **right**: [Mg/Fe] as a function of $E_{\rm exp}$ for all models. Square, triangle, and circle with a vertical error bar describe observed [Mg/Fe] in Cayrel *et al.* (2004), in Cayrel *et al.* (2004) with corrections of Andrievsky *et al.* (2008), in which NLTE effects are taken into account, and in Preston *et al.* (2006), respectively.

of comparable $E_{\rm exp}$. Moreover, [Mg/Fe] are found to roughly anti-correlate with $E_{\rm exp}$ (right panel in Fig. 1). The observed [Mg/Fe] of Cayrel *et al.* (2004) with the NLTE corrections of Andrievsky *et al.* (2008) (triangle with a vertical error bar) is comparable to [Mg/Fe] estimated for $M_{\rm ms} = 20, 25$ and $30 M_\odot$ and for models with $M_{\rm ms} = 15 M_\odot$ and $E_{\rm exp} \sim 0.5 \times 10^{51}$erg, in which ejected masses of ^{56}Ni are $0.02 - 0.03 M_\odot$. [Mg/Fe] for models with $M_{\rm ms} = 11 M_\odot$ and $M({\rm Fe}) > 0.005 M_\odot$ are lower than the observed [Mg/Fe]. Pop III SN of $M_{\rm ms} = 11$ and $15 M_\odot$ could be a faint SN. Also for models with $E_{\rm exp} > 10^{52}$erg [Mg/Fe] are lower than the observed ones.

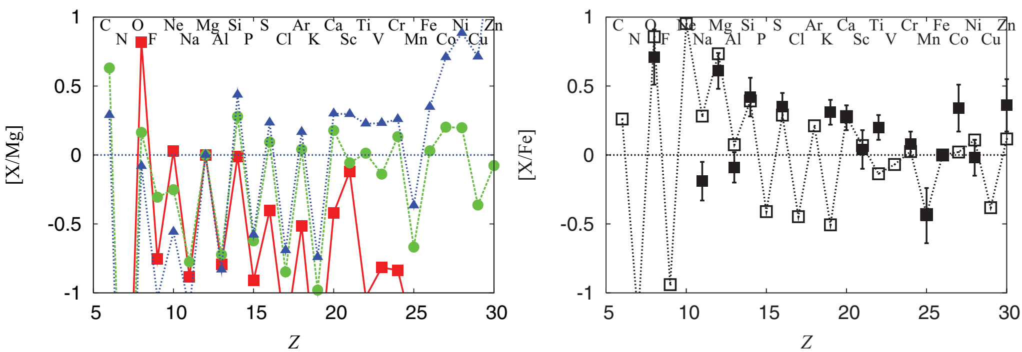

Figure 2. left: [X/Mg] as a function of Z of the SN ejecta for $M_{\rm ms} = 11 M_\odot$ and $E_{\rm exp} = 0.18 \times 10^{51}$erg (line with filled triangles), 0.19×10^{51}erg (line with filled circles) and 0.91×10^{51}erg (line with filled squares). **right**: IMF-averaged [X/Fe] as a function of Z (dotted line with squares) and averaged [X/Fe] observed in MPSs (filled squares). Here IMF-averaging is performed over models with $M_{\rm ms} = 11$, 15, 20, 25, 30, and 40 $M_\odot$ whose $E_{\rm exp}$ are 0.91, 1.00, 1.06, 1.24, 1.09, and 7.05 in units of 10^{51}erg, respectively.

Figure 2 shows [X/Mg] as a function of the atomic number Z of the SN ejecta for $M_{\rm ms} = 11 M_\odot$ (left panel), and [X/Fe] averaged with the Salpeter IMF as a function of Z as well as the average of observed abundance ratios in Cayrel *et al.* (2004) with the NLTE corrections of Andrievsky *et al.* (2008) (right panel).

We find that nuclei with $Z \geqslant 21$, which are underproduced in the aspherical model of Joggerst *et al.* (2010), are appreciably produced even for cases with lower explosion energies $E_{\rm exp} < 1 \times 10^{51}$erg (left panel in Fig. 2). Material mixing induced via SASI is

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therefore important for the enhancement of nuclei with $Z \geqslant 21$ in the SN ejecta, since the mixing via RT instabilities during the later explosion phase is taken into account in the aspherical model of Joggerst *et al.* (2010). Moreover, we find that the IMF-averaged [X/Fe] well reproduce the observed average ratio (solid line with filled squares in right panel), other than K, as in Tominaga *et al.* (2007) and Heger & Woosley (2010). Ti and Co are slightly underproduced, while [Na/Fe] is overproduced compared with the observed ratio because of large [Na/Fe] for $M_{\rm ms} \geqslant 15 M_{\odot}$.

4. Summary

We have investigated explosive nucleosynthesis during neutrino-driven, aspherical SN explosion aided by SASI, based on 2D hydrodynamic simulations of the explosion of six Pop III stars, whose masses are 11, 15, 20, 25, 30, and $40 M_{\odot}$. The magnitude and asymmetry of the explosion energy are estimated with the simulations, for a given set of neutrino luminosities and temperatures. By post-processing calculations with the large nuclear reaction network, we have evaluated abundances and masses of ejecta from the aspherical SNe.

We find that masses of Fe roughly correlate with the explosion energies, while [Mg/Fe] anti-correlate. Comparison between estimated and observed [Mg/Fe] suggests that Pop III SNe of a progenitor with lower mass ($\leqslant 15 M_{\odot}$) may be faint SNe. Nuclei with $Z \geqslant 21$, which are underproduced in the aspherical model of Joggerst *et al.* (2010), are appreciably produced. Material mixing induced via SASI is therefore important for the enhancement of nuclei with $Z \geqslant 21$ in the SN ejecta. Moreover, we evaluate IMF-averaged abundances using the abundances and masses of the ejecta in our 2D models. We find that the evaluated abundance ratios are similar to the averaged observed ratios in MPSs (Cayrel *et al.* (2004)), as shown in the spherical models by Tominaga *et al.* (2007) and Heger & Woosley (2010), although in their models, the explosion is manually and spherically initiated by means of a thermal bomb or a piston, and also artificial mixing procedures are required for the reproduction of the observed ratios. However, observed [K/Fe] cannot be reproduced with our 2D SN models.

References

Cayrel, R., Depagne, E., Spite, M., *et al.* 2004, *A&A*, 416, 1117
Tominaga, N., Umeda, H., & Nomoto, K. 2007, *ApJ*, 660, 516
Heger, A. & Woosley, S. E. 2010, *ApJ*, 724, 341
Joggerst, C. C., Woosley, S. E., & Heger, A. 2009, *ApJ*, 693, 1780
Joggerst, C. C., Almgren, A., Bell, J., *et al.* 2010, *ApJ*, 709, 11
Marek, A., & Janka, H.-T.2009, ApJ, 694, 664
Suwa, Y., Kotake, K., Takiwaki, T., Whitehouse, S., & Liebendörfer, M. 2010, *PASJ*, 62, L49.
Ohnishi, N., Kotake, K., & Yamada, S. 2006, *ApJ*, 641, 1018
Fujimoto, S., Hashimoto, M., Ono, M., & Kotake, K. 2011, *ApJ*, 738, 61
O'Connor, E. & Ott, C. D. 2011, *ApJ*, 730, 70
Andrievsky, S. M., Spite, M., Korotin, S. A., *et al.* 2008, *A&A*, 481, 481
Preston, G. W., Sneden, C., Thompson, I. B., *et al.* 2006, *AJ*, 132, 85

Discussion

K. Nomoto: Comment: Nucleosynthesis in hypernovae models is sensitive to the degree of fallback of material onto a black hole. Especially, the fallback of ^{56}Ni results in faint SNe and large [Mg/Fe] in your models.

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