Death of Massive Stars: Supernovae and Gamma-Ray Bursts
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Progenitor for Type Ic Supernova 2007bi

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Abstract. We investigate the evolution of very massive stars with $Z = 0.2Z_\odot$ to constrain the progenitor of the extremely luminous Type Ic SN 2007bi. In order to reproduce the ^{56}Ni amount produced in SN 2007bi, the range of the stellar mass at the zero-age main-sequence is expected to be $515 - 575M_\odot$ for pair-instability supernova and $110 - 280M_\odot$ for core-collapse supernova. Uncertainty in the mass loss rate affects the mass range appropriate for the explosion of SN 2007bi. A core-collapse supernova of a WO star evolved from a 110 $M_\odot$ star produces sufficient radioactive ^{56}Ni to reproduce the light curve of SN 2007bi.

Keywords. stars: evolution, stars: massive, supernovae: individual: SN 2007bi

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Introduction: SN 2007bi is one of the most luminous Type Ic supernova (SN). Light curve and spectrum analyses deduced that $3.6 - 7.4M_\odot$ of radioactive ^{56}Ni was ejected from this SN (Gal-Yam *et al.* 2009). Because of such a large production of radioactive ^{56}Ni, there are two possibilities proposed as the explosion mechanism reproducing the light curve of SN 2007bi. One is a pair-instability (PI) SN with a CO core progenitor of $\sim 100M_\odot$ (Gal-Yam *et al.* 2009). A core-collapse (CC) SN model of a $\sim 43M_\odot$ CO core progenitor and an explosion energy of $E_{\rm ex,51} = 30$, where $E_{\rm ex,51}$ is the explosion energy in units of 10^{51} erg, also reproduce the light curve of SN 2007bi (Moriya *et al.* 2010). The metallicity of the host galaxy is observationally evaluated as $Z = 0.2 - 0.4Z_\odot$ (Young *et al.* 2010). We calculate the evolution of very massive stars with $Z = 0.2Z_\odot$ and investigate the relation of the final mass, $M_{\rm f}$, the CO core mass, $M_{\rm CO}$, and the surface He abundance to the mass at the zero-age main sequence (MS), $M_{\rm MS}$, to constrain the explosion mechanism of SN 2007bi.

Evolution Model: We calculate the evolution of very massive stars with MS masses $M_{\rm MS} = 100 - 500M_\odot$ and metallicity $Z = 0.2Z_\odot$ until the carbon-burning. The mass loss rates in OB stars, red-giant branch, and Wolf-Rayet stars are taken into account. Details for the stellar evolution calculation are described in Yoshida & Umeda (2011).

Results and Discussion: We show the relation of the final mass and the CO core mass to the MS mass of the very massive stars in Figure 1(a). The final mass and the CO core mass increases with MS mass for this metallicity. The range of the CO core mass appropriate for PI explosion of SN 2007bi is evaluated to be $95 \leqslant M_{\rm CO} \leqslant 105M_\odot$ from Heger & Woosley (2002). We expect that more than 3 $M_\odot$ of ^{56}Ni is ejected from a CC SN if the CO core of the progenitor is larger than $35M_\odot$ and the explosion energy is larger than $E_{\rm ex,51} \geqslant 30$ (Umeda & Nomoto 2008). On the other hand, if the CO core is larger than 60 $M_\odot$, the star will explode as a PI SN (Heger & Woosley 2002, Umeda & Nomoto 2002). These ranges are shown by the shaded regions in this figure.

The range of the MS mass appropriate for PI explosion of SN 2007bi is larger than 500 $M_\odot$. The extrapolated range is evaluated to be $515 - 575M_\odot$. A star with this mass range is expected to evolve as a WO star. On the other hand, the MS mass range for CC explosion from a WO star is $110 - 280M_\odot$. We note that the mass loss rate of very massive stars is still uncertain. We also calculated the evolution of a very massive star by decreasing the mass loss rate by a factor of two throughout the evolution. In this case,

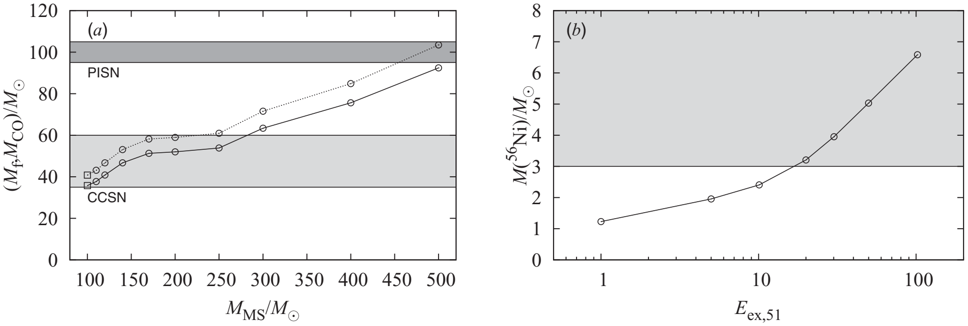

Figure 1. (*a*) The final mass (dashed line) and the CO core mass (solid line) relating to the MS mass. Squares and circles indicate the WN and WO stars at the final stage of the evolution. Dark and light shaded regions indicate the ranges of the CO core mass appropriate for PI and CC explosions of SN 2007bi. (*b*) The dependence of the ejected ^{56}Ni amount on the explosion energy of core-collapse SN evolved from the $M_{MS} = 110 M_\odot$ star.

the MS mass ranges appropriate for PI and CC explosions of SN 2007bi are $310 - 350 M_\odot$ and $135 - 170 M_\odot$, respectively.

The possible He amount hidden in a Type Ic SN is an unclarified problem. Although the stars with $M_{MS} \geqslant 110 M_\odot$ evolve to WO stars, small amount of He remains at the surface. The calculated WO stars have a surface He amount of $\sim 0.36 - 1.02 M_\odot$. Georgy *et al.* (2009) discussed that the choice of the He amount between 0.6 and 1.5 $M_\odot$ hardly affects the ranges of Type Ib/Ic SNe. The surface He mass fraction Y_s also may be a criterion. Yoon *et al.* (2010) discussed the criterion of $Y_s \leqslant 0.5$ for Type Ic SNe. The surface He mass fraction of the WO stars is smaller than 0.2, which satisfies the criterion. Recently, the possible He amount hidden in $\sim 1 M_\odot$ Type Ic SN ejecta was evaluated (Hachinger *et al.* 2012). A similar evaluation should be performed for more massive SNe.

We investigate the ^{56}Ni amount ejected from a CC SN evolved from a very massive star with $M_{MS} = 110 M_\odot$. This star evolves to a WO star with $M_f = 43.2 M_\odot$ and $M_{CO} = 38.2 M_\odot$. When the iron core is defined as the region where the mass fraction of iron-peak elements is larger than 0.5, the iron-core mass is 3.03 $M_\odot$. This star does not explode as a PI SN. Figure 1(*b*) shows the dependence of the ejected ^{56}Ni amount on the explosion energy. The ^{56}Ni amount increases with the explosion energy. When the explosion energy is larger than $E_{ex,51} \geqslant 20$, the ejected ^{56}Ni amount reproduces the ^{56}Ni yield of SN 2007bi. If a star has a MS mass larger than 110 $M_\odot$ and explodes with the same explosion energy, the ejected ^{56}Ni amount would be larger.

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