A progenitor for the extremely luminous Type Ic supernova 2007bi

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ABSTRACT
SN 2007bi is an extremely luminous Type Ic supernova. This supernova is thought to be evolved from a very massive star, and two possibilities have been proposed for the explosion mechanism. One possibility is a pair-instability supernova with an $M_{\text{CO}} \sim 100 \, M_\odot$ CO core progenitor. Another possibility is a core-collapse supernova with $M_{\text{CO}} \sim 40 \, M_\odot$. We investigate the evolution of very massive stars with main-sequence mass $M_{\text{MS}} = 100 - 500 \, M_\odot$ and $Z_0 = 0.004$, which is in the metallicity range of the host galaxy of SN 2007bi, to constrain the progenitor of SN 2007bi. The supernova type relating to the surface He abundance is also discussed. The main-sequence mass of the progenitor exploding as a pair-instability supernova could be $M_{\text{MS}} \sim 515 - 575 \, M_\odot$. The minimum main-sequence mass could be $310 \, M_\odot$ when uncertainties in the mass-loss rate are considered. A star with $M_{\text{MS}} \sim 110 - 280 \, M_\odot$ evolves to a CO star, appropriate for the core-collapse supernova of SN 2007bi. Arguments based on the probability of pair-instability and core-collapse supernovae favour the hypothesis that SN 2007bi originated from a core-collapse supernova event.

Key words: stars: evolution — stars: massive — stars: mass-loss — supernovae: individual: SN 2007bi — stars: Wolf-Rayet.

1 INTRODUCTION

SN 2007bi was found as an extremely luminous Type Ic supernova (SN Ic). Spectral analyses deduced the production of $3.6 - 7.4 \, M_\odot$ of radioactive $^{56}\text{Ni}$ (Gal-Yam et al. 2009). The metallicity of the host galaxy of SN 2007bi, which is a subluminous dwarf galaxy, has been observed to be $12 + \log(O/H) = 8.15 \pm 0.15$, corresponding to $Z = 0.2 - 0.4 \, Z_\odot$ (Young et al. 2010). This metallicity is similar to those of low-metallicity galaxies undergoing $\gamma$-ray bursts (GRBs) associated with SNe.

This SN was proposed as a pair-instability (PI) SN from observations of the light curve and spectral analyses. The final mass was estimated to be $\sim 100 \, M_\odot$. On the other hand, the light curve was also fitted by the energetic core-collapse (CC) explosion model (Moriya et al. 2010). The estimated progenitor was a $43 - M_\odot$ CO core. $40 \, M_\odot$ of ejecta, containing $6.1 \, M_\odot$ of $^{56}\text{Ni}$, were thought to be ejected. Although there is a difference in the rise period of the light curves of these models, there were no observations during the period. Hence, the explosion mechanism of SN 2007bi has not yet been clarified. Observational features such as the total $^{56}\text{Ni}$ mass and the SN type will provide constraints for the progenitor.

The evolution of very massive stars connects presupernova structures and stars at the main-sequence (MS) stage. The final stellar mass, the mass of the CO core and the surface composition depend on MS mass and metallicity through burning processes and mass loss. Calculations of the evolution of very massive stars will provide the relationship of these features to MS mass.

The relationship between the amount of $^{56}\text{Ni}$ produced in a SN and the CO core mass has been evaluated for PI and CC SN models. The mass range of the CO cores for PI SN progenitors has been evaluated as $M_{\text{CO}} \sim 60 - 130 \, M_\odot$ (Heger & Woosley 2002; Umeda & Nomoto 2002). Smaller progenitors for PI SNe were also suggested by Waldman (2008). The amount of $^{56}\text{Ni}$ produced in a PI SN increases with MS mass (Heger & Woosley 2002; Umeda & Nomoto 2002). The amount of $^{56}\text{Ni}$ ejected from a CC SN is related to the CO core mass and the explosion energy (Umeda & Nomoto 2008). A SN with an $M_{\text{CO}} \gtrsim 35 \, M_\odot$ progenitor can produce more than $3 \, M_\odot$ of $^{56}\text{Ni}$ when the explosion energy is $E_{\text{kin}} = 3 \times 10^{52}$ erg. These relations connect the amount of $^{56}\text{Ni}$ deduced from the observations of SN 2007bi with the theoretical MS mass of a very massive star.

In this Letter, we evaluate the mass range of very massive stars with initial metallicity of $Z_0 = 0.004$ ($= 0.2 \, Z_\odot$) appropriate for the progenitor of SN 2007bi. We calculate the evolution of very massive stars with MS mass range $M_{\text{MS}} = 100 - 500 \, M_\odot$ taking into account uncertainties in mass-loss rate. We show the CO core mass as a function of the MS mass. Then, we constrain the MS and CO core masses using the amount of $^{56}\text{Ni}$ observed in SN 2007bi. We also discuss the relationship between the SN type and surface He abundance. Finally, we deduce the ranges of MS mass in PI and CC SN models appropriate for SN 2007bi and discuss the possible explosion mechanism.

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2 PROGENITOR MODEL

2.1 Stellar evolution model

In order to estimate the progenitor mass of SN 2007bi, we calculated the evolution of very massive stars from H burning until central He exhaustion. We considered a mass range of zero-age MS stars of $M_{\text{MS}} = 100 - 500 \, M_\odot$. The initial metallicity was set to be $Z_0 = 0.004 = 0.2 \, Z_\odot$. The initial mass fractions of $^1\text{H}$ and $^4\text{He}$ were set to be 0.7492 and 0.2468, respectively. The relative abundances of species heavier than He were derived from Anders & Grevesse (1989).

The stellar evolution code was updated from Saio et al. (1988) and Umeda & Nomoto (2005). We used a nuclear reaction network consisting of 282 species of nuclei from n, p, to Br to calculate and Umeda & Nomoto (2005). We used a nuclear reaction network

The mass-loss rate of MS stars with effective temperature $T_{\text{eff}} > 12000 \, K$ and H mass fraction $X \geq 0.4$ was taken from Vink et al. (2001). The mass-loss rate of stars with low surface temperature $T_{\text{eff}} \leq 12000 \, K$ was adopted from de Jager et al. (1988). We multiplied the mass-loss rate by the metallicity dependence factor $(Z/Z_\odot)^{0.64}$. The power index 0.64 is the same value as that of B supergiants in Vink et al. (2001) and is consistent with observational scaling (Maeron & Josselin 2011).

We set the mass-loss rate of Wolf-Rayet (WR) stars with $T_{\text{eff}} > 12000 \, K$ and $X < 0.4$ as

$$\log(-\dot{M}) = -11.0 + 1.29 \log(L/L_\odot) + 1.73 \log \min(Y_\odot, 0.98) + 0.47 \log \max(Z, 0.02) + \alpha \log(Z_0/0.02) \left[\log(M_\odot \text{yr}^{-1})\right],$$

(1)

where $L$ and $Y_\odot$ are the luminosity and helium mass fraction at the surface. The factor for the initial metallicity dependence $\alpha$ was set to be 0.86 and 0.66 for WN and WC stars, respectively. WR stars were classified into WN, WC and WO stars in accordance with Geoffrey et al. (2009). We took into account equation (22) in Nugis & Lamers (2000) and the initial-metallicity dependence in Vink & de Koter (2005). Extreme, episodic mass loss in WR stars, which has been observed in some SNe (e.g. Foley et al. 2007, for SN 2006jc) was not taken into account in the present study.

2.2 Mass-loss rate

Since mass-loss rates suffer from various uncertainties, we present models computed with the following three different mass-loss recipes.

2.2.1 Case A (standard case)

The mass-loss rate of MS stars with effective temperature $T_{\text{eff}} > 12\,000 \, K$ and H mass fraction $X \geq 0.4$ was taken from Vink et al. (2001). The mass-loss rate of stars with low surface temperature $T_{\text{eff}} \leq 12\,000 \, K$ was adopted from de Jager et al. (1988). We multiplied the mass-loss rate by the metallicity dependence factor $(Z/Z_\odot)^{0.64}$. The power index 0.64 is the same value as that of B supergiants in Vink et al. (2001) and is consistent with observational scaling (Maeron & Josselin 2011).

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2.2.2 Case B (larger mass loss during the WR phase)

We adopted the same mass-loss rates in the MS and low surface temperature phases, and rates with metallicity-dependent indices $\alpha = 0.60$ and 0.40 for WN and WC stars, respectively. The metallicity dependence of the mass-loss rate of WR stars in the Large Magellanic Cloud and Small Magellanic Cloud was observed as $\propto (Z_0/Z_\odot)^{0.8 \pm 0.2}$ for WN stars and $\propto (Z_0/Z_\odot)^{0.6 \pm 0.2}$ for WC stars (Crowther 2007). If the scaling index is small, the corresponding mass-loss rate is large.

2.2.3 Case C (smaller mass loss during whole lifetime)

We reduced the mass-loss rate in case A by a factor of 2 during the whole lifetime. Overestimations of the empirical mass-loss rate in OB stars and WR stars have been discussed (see the review in Crowther 2007, Pulse et al. 2008). The reduction of mass-loss rate depends on wind clumping (e.g. Fullerton et al. 2006, Mokiem et al. 2007), and the degree of clumping has large uncertainties (Pulse et al. 2008). It is considered that a reduction within a factor of 2 from the theoretical evaluation (Vink et al. 2001) is allowed from stellar evolution models (Hirschi 2008, Pulse et al. 2008). The effect of wind clumping in WR stars was taken into account by Nugis & Lamers (2000). The reduction of global mass-loss rate of WR stars by wind clumping is a factor of 2 – 4 relative to the homogeneous model (Crowther 2007). The surface temperature of very massive stars does not decrease to log $T_{\text{eff}} < 3.6$, and dust-driven winds might be ineffective. In this case, wind clumping might be effective for low surface temperature.

3 RESULTS

3.1 Final mass of very massive stars

Fig. 1(a) shows the final mass $M_f$ and type of WR star as a function of the MS mass. The final progenitor mass depends on the mass-loss rate as well as on the MS mass. The dependence on the mass-loss rate is larger for more massive stellar models. In case A the final mass increases with the MS mass. These stars evolve to WR stars except for the one with $M_{MS} = 100 \, M_\odot$. The final mass of the stars in case B rises with the MS mass except for the range of $170 \lesssim M_{MS} \lesssim 250 \, M_\odot$. All of the stars evolve to WR stars. The increasing final mass is also shown in case C. The final type of the star depends on the MS mass. The relatively ‘low’-mass stars with $100 \lesssim M_{MS} \lesssim 120 \, M_\odot$ evolve to WN stars. The stars with $130 \lesssim M_{MS} \lesssim 140 \, M_\odot$ and $200 \lesssim M_{MS} \lesssim 300 \, M_\odot$ evolve to WC stars. The former WC stars lose their remaining He envelope during carbon burning. The He envelope of the latter stars has mostly been stripped away before carbon burning. The other stars evolve to WR stars.

The mass of the CO core of an evolved star is important for the explosion mechanism of SN 2007bi. Fig. 1(b) shows the CO core mass $M_{CO}$ as a function of the MS mass. The mass of the CO core is defined as the largest mass coordinate satisfying a Hemass $\approx 0.02$ for WC stars and $\approx 0.03$ for WC stars (Crowther 2007). If the scaling index is small, the corresponding mass-loss rate is large.

3.2 Ejected amount of $^{56}\text{Ni}$ and mass of CO core

From analyses of the light curve and spectra of SN 2007bi, the ejection of $3.6 - 7.4 \, M_\odot$ of $^{56}\text{Ni}$ has been derived. The average amount of $^{56}\text{Ni}$ is $5.3 \, M_\odot$. The amount of ejected $^{56}\text{Ni}$ has been connected to the CO core mass in previous studies. Here we constrain the range of MS mass from the amount of $^{56}\text{Ni}$ in SN 2007bi.
as a PI SN and a CC SN, respectively.

Figure 1. The final mass (a) and CO core mass (b) as a function of the MS mass. Solid, dashed, and dotted lines correspond to cases A, B and C, respectively. Squares, triangles, crosses and circles indicate WN, 'He-rich' WC (see Section 3.3), WC and WO stars. Dark and light shaded regions denote the mass ranges of the CO cores appropriate for SN 2007bi to explode as a PI SN and a CC SN, respectively.

Nucleosynthesis studies of PI SNe have indicated that PI SN models with $95 \lesssim M_{\text{CO}} \lesssim 105 M_\odot$ produce $3 \sim 10 M_\odot$ of $^{56}\text{Ni}$ (Heger & Woosley 2002). The PI SN models of Umeda & Nomoto (2002) obtained a similar result. Therefore the progenitor of the PI SN corresponding to SN 2007bi should be a CO core with $95 \lesssim M_{\text{CO}} \lesssim 105 M_\odot$.

The MS mass range deduced from the CO core mass is shown as the dark shaded region in Fig. 1(b). This criterion is not satisfied in cases A and B. The MS mass range in case A is estimated to be $515 \lesssim M_{\text{MS}} \lesssim 575 M_\odot$ from linear extrapolation in Fig. 1(b). In case C, the appropriate range reduces to $310 \lesssim M_{\text{MS}} \lesssim 350 M_\odot$.

The amount of $^{56}\text{Ni}$ produced in a CC SN model gives a lower limit on the progenitor mass. We expect from the result of Umeda & Nomoto (2008) that a SN with a kinetic energy of $\sim 3 \times 10^{52}$ erg can produce more than $3 M_\odot$ of $^{56}\text{Ni}$ if the CO core of the progenitor is larger than $\sim 35 M_\odot$. The upper limit of the MS mass might be the lowest mass of a PI SN progenitor. Theoretical studies of PI SNe have indicated that a CO core larger than $\gtrsim 60 M_\odot$ explodes as a PI SN (Heger & Woosley 2002, Umeda & Nomoto 2002). We consider the upper limit of a CC SN progenitor as $\sim 60 M_\odot$. Therefore, the CO core mass appropriate for explaining SN 2007bi with a CC explosion is $35 \lesssim M_{\text{CO}} \lesssim 60 M_\odot$.

3.3 Surface He abundance for SNe Ib/Ic

SNe Ic are characterized by weak or absent He spectra. However, a quantitative criterion to distinguish between SNe Ib and Ic has not been theoretically established. The He lines are considered to appear because of the excitation of He by non-thermal electrons excited by $\gamma$-rays from the decays of $^{56}\text{Ni}$ and $^{56}\text{Co}$ (Lucy 1991). The strength of the He lines should be sensitive to the amounts of He and $^{56}\text{Ni}$, the amount of matter in intermediate layers between Ni and He layers which attenuate the $\gamma$-rays, the degree of mixing of Ni into He layer, etc. Criteria to distinguish between SNe Ib and Ic were discussed using the total He mass of a progenitor (Wellstein & Langer 1999, Georgy et al. 2009, Yoon et al. 2010) or the He mass fraction at the outermost layers (Yoon et al. 2010). The effects of thickness of the intermediate layers and the degree of mixing have been investigated (Woosley & Eastman 1997). We discuss the possibility of a SN Ic progenitor by considering the total He mass, the He mass fraction at the surface and the mass ratio of He to the intermediate layers.

The first criterion is based on the total He mass. We consider two cases for the He mass limit of SNe Ic: 0.5 and 1.5 $M_\odot$. In previous studies, the He mass limit of SNe Ic was assumed to be 0.5 $M_\odot$ (Wellstein & Langer 1999, Yoon et al. 2010) or 0.6 $M_\odot$ (Georgy et al. 2009). On the other hand, Georgy et al. (2009) reported that the choice of the total He mass limit between 0.6 and 1.5 $M_\odot$ hardly affects the $M_{\text{MS}}$ ranges for SNe Ib/Ic. Yoon et al. (2010) suggested in discussion that He lines are not seen in early-time spectra even though the total He mass is as large as 1.0 $M_\odot$ if He is well mixed with CO material having $Y_s \lesssim 0.5$. Fig. 2(a) shows the total He mass versus the MS mass. When the He mass limit is 0.5 $M_\odot$, the MS mass is limited in the very narrow range of $110 \sim 120 M_\odot$ in case A and $100 \sim 115 M_\odot$ in case B. In case C no progenitors explode as SNe Ic. When the He mass limit is 1.5 $M_\odot$, all progenitors except for WN stars, an 'He-rich' WC star with $M_{\text{MS}} = 130 M_\odot$ in case C, and stars with $M_{\text{MS}} > 350 M_\odot$ in case C will explode as SNe Ic.

The second criterion is the He mass fraction at the surface. We set this criterion as $Y_s \lesssim 0.5$ in accordance with the discussion in Yoon et al. (2010) as mentioned above. Fig. 2(b) presents the He mass fraction at the surface as a function of the MS mass. All WN stars and WC stars except for the He-rich WC star will explode as SNe Ic.

We also consider the mass ratio of He to the intermediate layers. The mass of the intermediate layers is assumed to be $M_{\text{int}} = M_{\text{MC}} - 9.0 M_\odot$. The mass of 9.0 $M_\odot$ corresponds to the amount of ejected $^{56}\text{Ni}$ and the central remnant in the CC SN model. The masses of $^{56}\text{Ni}$ and the central remnant were evaluated to be 6.1 and 3.0 $M_\odot$, respectively, for the $43-9.0 M_\odot$ progenitor (Moriya et al. 2010). Although the amount of $^{56}\text{Ni}$ would be smaller than 9 $M_\odot$ and there is no remnant in the PI SN model, the difference is not important because the final mass of the PI SN progenitors is $\sim 100 M_\odot$. The mass ratio of He to the intermediate layers is shown in Fig. 2(c). The ratios of WN stars and the He-rich WC star are clearly larger than those of WO and the other WC stars. We may set the criterion of the ratio as $\sim 0.02 \sim 0.03$. In this case, the range of
The total He mass in the envelope (a), the He mass fraction at the surface (b), and the mass ratio of He to the intermediate layers (c) plotted against the MS mass. Solid, dashed and dotted lines correspond to cases A, B and C, respectively. Squares, triangles, crosses and circles indicate WN, ‘He-rich’ WC, WC and WO stars. In panel (a), dark and light shaded regions satisfy the criteria \( M(He) \leq 0.5 M_\odot \) or \( Y_s \leq 0.5 \), respectively. In panel (b), the shaded region satisfies the criterion \( Y_s \leq 0.5 \).

MS mass is the same as that deduced from the criterion of the He mass fraction at the surface.

**Table 1.** The range of MS mass for PI and CC SN models appropriate for SN 2007bi deduced from the mass range of the CO core and the surface He abundance. The ratio of the probability of explosion as a PI SN to explosion as a CC SN for SN 2007bi, \( r_{PI/CC} \), is also listed (see Section 4).

| Condition | PI SN (\( M_{MS} \)) | CC SN (\( M_{MS} \)) | \( r_{PI/CC} \) |
|-----------|---------------------|---------------------|----------------|
| Case A    |                     |                     | 0              |
| \( M(He) \leq 0.5 M_\odot \) or \( Y_s \leq 0.5 \) | 110 – 220 \( M_\odot \) | 0              |
| Case B    |                     |                     | 0.024          |
| \( M(He) \leq 0.5 M_\odot \) or \( Y_s \leq 0.5 \) | 575 – 775 \( M_\odot \) | 110 – 240 \( M_\odot \) |
| Case C    |                     |                     | 0              |
| \( M(He) \leq 0.5 M_\odot \) or \( Y_s \leq 0.5 \) | 110 – 115 \( M_\odot \) | 110 – 500 \( M_\odot \) |
| \( M(He) \leq 0.5 M_\odot \) or \( Y_s \leq 0.5 \) | 100 – 180 \( M_\odot \) | 135 – 170 \( M_\odot \) |

**5 CONCLUDING REMARKS**

We have investigated the evolution of very massive stars with mass \( M_{MS} = 100 – 500 M_\odot \) and \( Z = 0.004 \) from H burning to central He exhaustion to constrain the progenitor of an extremely luminous Type Ic SN 2007bi. If SN 2007bi is a PI SN, the progenitor could be evolved from a MS star with \( 515 \leq M_{MS} \leq 575 M_\odot \). If SN 2007bi is a CC SN, the appropriate range of the MS mass is \( 110 \leq M_{MS} \leq 280 M_\odot \). When we take into account a Salpeter IMF, the
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probability of SN 2007bi exploding as a CC SN is about 40 times larger than for a PI SN. If the mass-loss rate is small, the minimum mass for the progenitor becoming a PI SN is about 310 $M_\odot$. The mass range changes to $M_{MS} \sim 310 - 350 M_\odot$ for the PI SN model and $M_{MS} \sim 135 - 170 M_\odot$ for the CC SN model. If the mass-loss rate is large or He lines appear for an He mass of $M(He) > 0.5 M_\odot$, then SN 2007bi should have exploded as a CC SN. Although the light curve of SN 2007bi was fitted by both the PI SN and CC SN models, the CC SN model is favoured as explaining the explosion of SN 2007bi from arguments based on the probability ratio of the PI SN model appropriate for SN 2007bi to the CC SN model.

We should note that the conditions of He abundance for the progenitor to become a Type Ic SN strongly affect the probability of a PI SN. If a total He mass $M(He) > 0.5 M_\odot$ enables the formation of He spectra, the PI SN model would be inadequate for SN 2007bi even for a small mass-loss rate. It is quite important to evaluate more definite criteria to classify SNe Ic. We also note the probability of direct collapse without bright SNe for CC SN cases. This would reduce the probability of a CC SN for SN 2007bi. It is necessary to evaluate theoretically or observationally the fraction of black hole formation without bright SNe in CC SNe.

If the progenitor of SN 2007bi or a more massive star was rotating very fast, it could explode as a SN Ic associated with a GRB. We may not have seen such a GRB-SN because of the orientation effect. This is also interesting point to investigate in the future.

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