Progenitor for Type Ic Supernova 2007bi

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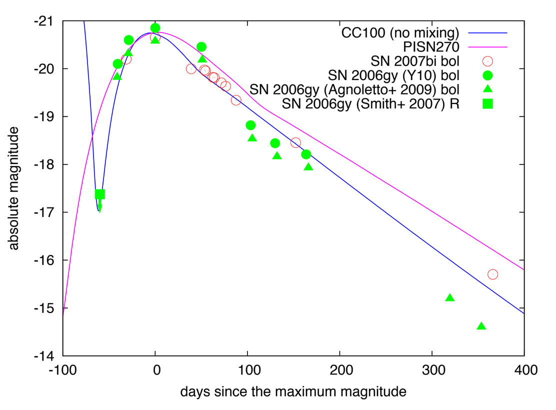
SN 2007bi is an extremely luminous Type Ic supernova. This supernova is thought to be evolved from a very massive star and two possibilities of explosion mechanism have been proposed. One possibility is a pair-instability supernova with a $M_{CO} \sim 100 M_\odot$ CO core progenitor. Another possibility is a core-collapse supernova with a $M_{CO} \sim 40 M_\odot$. We investigate the evolution of very massive stars with main-sequence mass M_{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_{MS} ~ 515 - 575 $M_\odot$. The minimum mass could be 310 $M_\odot$ when uncertainties in the mass loss rate are considered. A star with M_{MS} ~ 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 favor the hypothesis that SN 2007bi originated from a core-collapse supernova event.

SN 2007bi

Identification of SN 2007bi on 2007 April 6.5 UT

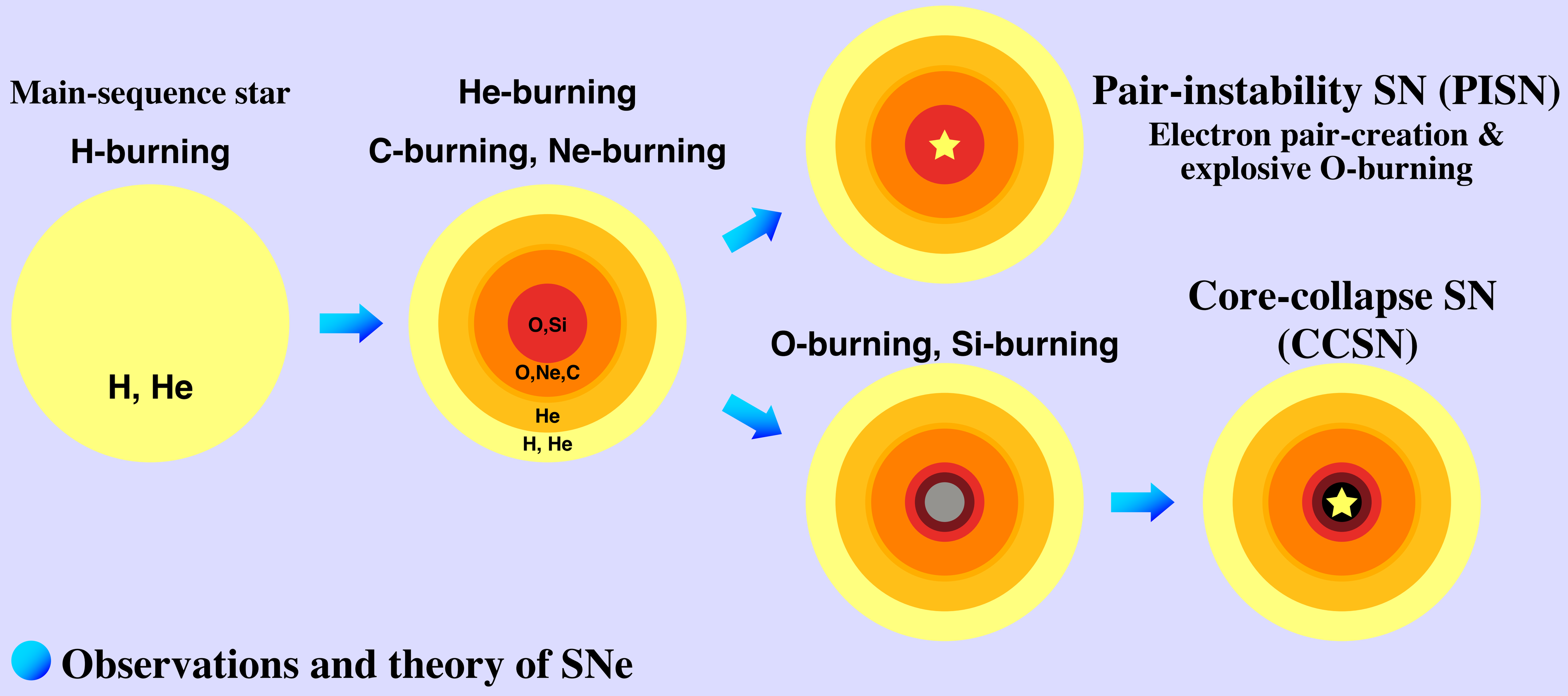


Light curve of SN 2007bi. This figure is reprinted from Fig. 3 in Moriya et al. (2010). ○ denotes the observational value of the light curve (Young et al. 2010). Red and blue lines are the light curves evaluated using pair-instability SN and core-collapse SN models, respectively.

Observational features of SN 2007bi (Gal-Yam et al. 2009)

- Peak R-band absolute magnitude
  - ➡ M_R = -21.3 mag
- ^{56}Ni amount evaluated from spectral analyses
  - ➡ $M(^{56}Ni)$ = 3.7 - 7.4 $M_\odot$
- Metallicity of the host galaxy (Young et al. 2010)
  - ➡ Z ~ 0.004 - 0.008 (0.2 - 0.4 $Z_\odot$)

Pair-Instability SN vs Core-Collapse SN



- M_{CO} condition for SN 2007bi
  - $M(^{56}Ni)$ = 3 - 10 $M_\odot$
  - ➡ M_{CO} ~ 95 - 105 $M_\odot$ (Heger & Woosley 2002; Umeda & Nomoto 2002)
- M_{CO} condition for SN 2007bi
  - M_{CO} > 35 $M_\odot$, E_{kin} ~ 3□10^{52} ergs
  - → $M(^{56}Ni)$ > 3 $M_\odot$ (Umeda & Nomoto 2008)
  - M_{CO} > 60 $M_\odot$ → PISN (Heger & Woosley 2002; Umeda & Nomoto 2002)
  - ➡ M_{CO} ~ 35 - 60 $M_\odot$

- Observations and theory of SNe
  - ➡ Relation among the amount of ^{56}Ni, $M(^{56}Ni)$, the mass of CO core, M_{CO}, and SN type
- Theory of stellar evolution
  - ➡ Relation among the main sequence mass, M_{MS}, the mass of CO core, M_{CO}, and surface abundance of He

Purpose: Investigation of the evolution of very massive stars to constrain the explosion mechanism of SN 2007bi

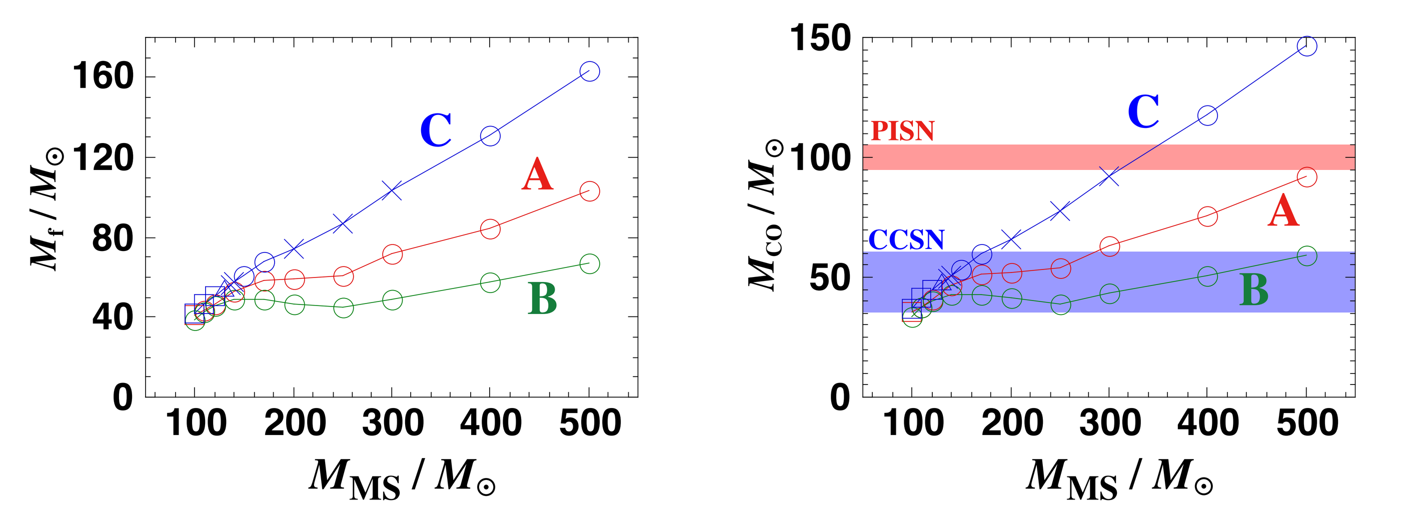
Model of Very Massive Stars

Model of very massive stars (Updated from Saio et al. 1988; Umeda & Nomoto 2008)

- 100 $M_\odot \le M_{MS} \le$ 500 $M_\odot$, Z_0 = 0.004
- From the main-sequence (MS) stage to C-burning
- Chemical compositions and energy generation
  - ➡ Nuclear reaction network; n, H~Br (282 nuclei)
- Mass loss rate → 3 cases including uncertainties
  - ➡ **Case A: standard mass loss**
    - MS stars: Vink et al. (2001)
    - Red giants: de Jager et al. (1988), metallicity dependence from Vink et al. (2001)
    - Wolf-Rayet stars: Nugis & Lamers (2000), metallicity dependence from Vink & de Koter (2005)
  - ➡ **Case B: large mass loss**
    - Mass loss rate of Wolf-Rayet stars is adopted from the upper limit in Crowther (2007).
  - ➡ **Case C: small mass loss**
    - Mass loss rate during whole life time is a half of that in Case A (e.g., Crowther 2007).

Final Mass & CO Core Mass of Very Massive Stars

Relation among the MS mass, M_{MS}, the final mass, M_f, and the mass of CO core, M_{CO}



Red, green, and blue lines correspond to the mass loss rates in cases A, B, and C, respectively. Squares, triangles, crosses, and circles indicate WN, "He-rich" WC, WC, and WO stars. Red and blue shaded regions are the mass ranges of the CO cores appropriate for SN 2007bi to explode as a PISN and CCSN, respectively.

WN stars: H or He rich at the surface
N(N) > N(C,O)

WC stars: N(C,O) > N(N) at the surface

WO stars: N(C,O) > N(He) at the surface

- Pair-instability SN
  - Case A M_{MS} ~ 515 - 575 $M_\odot$ (Extrapolation from numerical results)
  - Case B No M_{MS} range appropriate for SN 2007bi
  - Case C M_{MS} ~ 310 - 350 $M_\odot$
- Core-collapse SN
  - Case A M_{MS} ~ 100 - 280 $M_\odot$
  - Case B M_{MS} ~ 110 - 500 $M_\odot$
  - Case C M_{MS} ~ 100 - 170 $M_\odot$

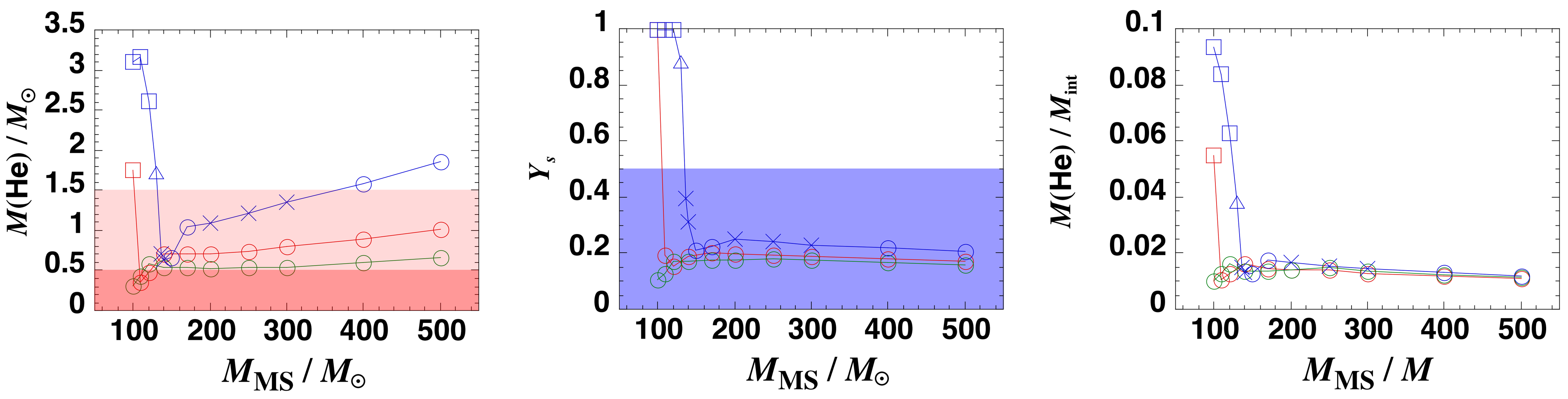
Surface He Amount

Type Ic SNe ➡ weak or absent He spectra

Criteria recognized as Type Ic have not been theoretically established.

Conditions of the He abundance discussed in the present study

- Total He mass ➡ M(He) < 0.5 $M_\odot$ or 1.5 $M_\odot$ (Georgy et al. 2009; Yoon et al. 2010)
- Mass fraction of He at the surface ➡ Y_s < 0.5 (Yoon et al. 2010)
- Mass ratio of He to intermediate layers M(He) / M_{int} (Woosley & Eastman 1997)



(Left) total He mass, (center) mass fraction of He at the surface, (right) mass ratio of He to intermediate layers as a function of the MS mass. Red, green, and blue lines correspond to the mass loss rates in cases A, B, and C, respectively. □, △, ×, and ○ indicate WN, "He-rich" WC, WC, and WO stars. Dark and light red regions in the left panel indicate M(He) < 0.5 $M_\odot$ and 1.5 $M_\odot$. Blue region in the middle panel corresponds to Y_s < 0.5. M_{int} is assumed to be M_f - 9 $M_\odot$.

- M(He) < 0.5 $M_\odot$ ➡ SN 2007bi should be the explosion as a CCSN.
- M(He) < 1.5 $M_\odot$ or Y_s < 0.5 ➡ The range of the MS mass is determined from the mass of CO core.

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Concluding Remarks

- The range of the MS range consistent with the explosion of SN 2007bi
  - ⬅ Considering ^{56}Ni yield and He abundance at the surface

Condition of He abundance	PISN	CCSN	$r_{PI/CC}$
Case A			
M(He) < 0.5 $M_\odot$	-	110 - 120 $M_\odot$	0
M(He) < 1.5 $M_\odot$ or Y_s < 0.5	515 - 575 $M_\odot$	110 - 280 $M_\odot$	0.024
Case B			
M(He) < 0.5 $M_\odot$	-	110 - 115 $M_\odot$	0
M(He) < 1.5 $M_\odot$ or Y_s < 0.5	-	110 - 500 $M_\odot$	0
Case C			
M(He) < 0.5 $M_\odot$	-	-	0
M(He) < 1.5 $M_\odot$ or Y_s < 0.5	310 - 350 $M_\odot$	135 - 170 $M_\odot$	0.19

- PPSN/CCSN population ratio $r_{PI/CC}$ derived using Salpeter IMF
  - ➡ $r_{PI/CC}$ ~ 0.024 - 0.19 (The cases where the explosion of PISN is possible)
  - The probability of SN 2007bi exploding as a CCSN is larger.
- Condition of He abundance for SN 2007bi to explode as a Type Ic SN
  - ➡ The probability of Type Ic PISNe is strongly sensitive to the condition.
  - It is important to evaluate definite criteria to classify into SN Ic.
- Possibility of direct collapse without bright SNe
  - ➡ The decrease in the probability of the explosion as a CCSN
  - It is necessary to evaluate theoretically or observationally the probability of direct collapse without bright SNe in CCSNe.