A CORE-COLLAPSE SUPERNOVA MODEL FOR THE EXTREMELY LUMINOUS TYPE Ic SUPERNOVA 2007bi: AN ALTERNATIVE TO THE PAIR-INSTABILITY SUPERNOVA MODEL

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Abstract

We present a core-collapse supernova (SN) model for the extremely luminous Type Ic SN 2007bi. By performing numerical calculations of hydrodynamics, nucleosynthesis, and radiation transport, we find that SN 2007bi is consistent with the core-collapse SN explosion of a 43 $M_\odot$ carbon and oxygen core obtained from the evolution of a progenitor star with a main-sequence mass of 100 $M_\odot$ and metallicity of $Z = Z_\odot/200$, from which its hydrogen and helium envelopes are artificially stripped. The ejecta mass and the ejecta kinetic energy of the models are 40 $M_\odot$ and 3.6 x 10^52 erg. The ejected 56Ni mass is as large as 6.1 $M_\odot$, which results from the explosive nucleosynthesis with large explosion energy. We also confirm that SN 2007bi is consistent with a pair-instability SN model as has recently been claimed. We show that the earlier light-curve data can discriminate between the models for such luminous SNe.

Key words: gamma-ray burst: general – supernovae: general – supernovae: individual (SN 2007bi, SN 2006gy)

Online-only material: color figures

1. INTRODUCTION

A massive star with the main-sequence mass ($M_{MS}$) in the range of 10–140 $M_\odot$ forms an Fe core in its center and eventually collapses. This collapse is thought to end up with the core-collapse supernova (SN) of Type II, Ib, or Ic (Filippenko 1997 for a review). If a star is as massive as $M_{MS} \approx 140–300 M_\odot$, the oxygen-rich core becomes dynamically unstable owing to the electron–positron pair creations (Rakavy & Shaviv 1967; Barkat et al. 1967). As the internal energy is spent by the pair creations, the core loses the stability and starts to collapse. When the central temperature exceeds $\sim 5 \times 10^9$ K, the core becomes stable but the temperature is so high that oxygen burning becomes explosive, producing enough energy to unbind the star. A large amount of 56Ni is synthesized by the explosive burning (e.g., Umeda & Nomoto 2002, hereafter UN02; Heger & Woosley 2002) and the subsequent radioactive decays power the light curve (LC). Thus, this event is theoretically predicted to be observed as a pair-instability supernova (PISN). Some luminous SNe, like SN 2006gy (Ofek et al. 2007; Smith et al. 2007), have been suggested to be PISNe (see Section 4.2), but no clear consensus has been reached (e.g., Kawabata et al. 2009).

Recently, Gal-Yam et al. (2009, hereafter G09) suggested that the extremely luminous Type Ic SN 2007bi is the first observed example of a PISN. They showed that the PISN model is consistent with the observed LC and the nebular spectra of SN 2007bi. They estimated the masses of C, O, Na, Mg, Ca, and 56Ni from the observed optical spectra. Other elements with no strong emission lines in the optical range, Si and S, are assumed to be the same as the PISN model of Heger & Woosley (2002). Young et al. (2010, hereafter Y10) showed multi-color observations of SN 2007bi and the metallicity of the host galaxy. However, the above observations of SN 2007bi have not quantitatively been compared with the core-collapse SN models. In view of the importance of clarifying the final fates of very massive stars, we examine how strong the observational constraints on the theoretical models are.

The aim of this Letter is to show that a core-collapse SN model is indeed consistent with the observed properties of SN 2007bi, if the progenitor is as massive as $M_{MS} \sim 100 M_\odot$ and the explosion energy is large. This would imply that SN 2007bi might not necessarily be a PISN. In Section 2, we summarize the progenitor models for SN 2007bi and numerical methods used for our calculations of hydrodynamics, nucleosynthesis, and the LC. The core-collapse SN models of SN 2007bi are presented in Section 3, and the results are discussed in Section 4.

2. PROGENITOR AND EXPLOSION MODELING

2.1. Progenitor

The high peak luminosity and the long rise time of the LC of SN 2007bi (G09, Y10) require a large amount of 56Ni (> 3 $M_\odot$, G09) and a large ejecta mass. These observations imply that the progenitor of SN 2007bi is massive. We apply a pre-SN model with $M_{MS} = 100 M_\odot$ calculated by Umeda & Nomoto (2008, hereafter UN08). UN08 assumed the metallicity of the progenitor models to be $Z = Z_\odot/200$, which is small enough to avoid a large amount of wind mass loss. Then the pre-SN model remains as massive as $M = 83 M_\odot$, whose carbon + oxygen (C+O) core is massive enough (43 $M_\odot$) to produce a large amount of 56Ni.

However, the pre-SN model has a massive H-rich envelope, while SN 2007bi does not show the lines of either H or He. Therefore, the progenitor must have lost its H-rich envelope (36 $M_\odot$) and He layer (4 $M_\odot$) during the pre-SN evolution, thus having only the bare C+O core at the explosion. We construct the pre-SN C+O star model of 43 $M_\odot$, by removing the H-rich envelope and He layer from the 83 $M_\odot$ star. Note that the metallicity of the host galaxy of SN 2007bi ($Z \sim Z_\odot/3$; Y10) is higher than that of our adopted progenitor ($Z = Z_\odot/200$). The wind mass loss is expected to work more efficiently, and the main-sequence mass of the progenitor, which has the C+O core mass of 43 $M_\odot$, might be more massive. The rotation of stars can also play a role in the mass loss (e.g., Meynet & Maeder...
This assumption of the positron absorption does not have much effect on the LCs we show in this Letter, because the contribution from the gamma rays is still a dominant energy source for them.

...
line cooling processes. In order to confirm that the abundances of the core-collapse SN model are consistent with the nebular spectra, we have to perform spectral synthesis calculations for the realistic hydrodynamical model of ejecta rather than the single-zone adopted by G09. As Si and S have many emission lines in the infrared range, infrared spectra are also helpful to distinguish PISNe from core-collapse SNe. We also point out that, if SN 2007bi is confirmed to be a PISN, we could expect that PISNe played a role in the chemical enrichment in the early universe and there should be some old stars with chemical compositions expected from PISNe, although they are still undiscovered (e.g., Cayrel et al. 2004).

4. CONCLUSIONS AND DISCUSSION

In this Letter, we have shown that the LC and the photospheric velocity of SN 2007bi are well reproduced by the core-collapse SN model CC100. As some gamma-ray bursts are connected to such high-energy Type Ic SNe, the extremely luminous SNe like SN 2007bi could also be connected to gamma-ray bursts which result from very massive stars. If this is the case, the extremely luminous SNe like SN 2007bi could be connected to gamma-ray bursts of much more massive star origin than known SNe associated with a gamma-ray burst. Even stars more massive than 300 $M_\odot$ could be the origin of luminous SNe (e.g., Ohkubo et al. 2006, 2009).

We note, however, that, although SN 2007bi may not necessarily be a PISN, the observational data available for SN 2007bi is not sufficient to single out the explosion mechanism. In fact, Kasen & Bildsten (2009) suggested that the magnetar-powered LC model (also, Maeda et al. 2007; Woosley 2009) might explain the LC of SN 2007bi.

Here, we show the comparison between our PISN model and SN 2007bi and discuss how to distinguish the models for luminous SNe. We also apply such LC comparison to SN 2006gy.

4.1. PISN Models for SN 2007bi

In Section 3 (Figure 1), we have shown that observations of SN 2007bi are well reproduced by the core-collapse SN model (CC100). Here, we confirm the claim made by G09 that a PISN model can also be consistent with the bolometric LC of SN 2007bi by using the approximate PISN model PISN270.

The PISN270 model is constructed by scaling the physical structure of the homologously expanding model CC100 to the ejecta model with $M_{ej} = 121 M_\odot$ and $E_{kin} = 7 \times 10^{52}$ erg. The ejecta mass $M_{ej}$ is the same as the C+O core mass of the PISN model with $M_{MS} = 270 M_\odot$ (UN02), and $E_{kin}$ is obtained from the nuclear energy released by explosive nuclear burning of the C+O core (UN02). Here, the same amount of $^{56}$Ni ($M_{56Ni} = 9.8 M_\odot$), as in the 270 $M_\odot$ model (UN02), is assumed to be synthesized in the inner layers. Note that the 270 $M_\odot$ model of UN02 still has the H-rich and He envelopes at the time of explosion and, here, we assume that the envelopes were stripped off by some mechanism.

Figure 3 shows that the bolometric LC of PISN270 (the red line) is consistent with the bolometric LC of SN 2007bi (red open circles). The rise time to the LC peak for PISN270 is $\sim 150$ days, being consistent with the PISN model in G09. This rise time is longer than the core-collapse SN model CC100 (Figure 3), because the photon diffusion takes more time in the more massive PISN270. Although $M_{56Ni}$ of PISN270 is $\sim 1.6$ times larger than that of the core-collapse SN CC100 model, the longer rise time lowers the peak brightness powered by the radioactive decay. These two effects make the peak magnitude of PISN270 similar to that of CC100.

This difference in the rising part of the LC is important for discriminating between the core-collapse SN and the PISN models. Although SN 2007bi was not observed early enough, much earlier observations before the peak could constrain the SN type from the LC. In addition, as already mentioned in Section 3, the abundance of Si and S would also be a key to distinguish between the two models.

4.2. Models for SN 2006gy

As mentioned in Section 1, there has been some suggestions that the luminous Type IIn SN 2006gy is a PISN (e.g., Smith et al. 2007). We thus apply our LC models for comparison with SN 2006gy. Figure 3 shows the bolometric LC of SN 2006gy.
(filled circles and triangles). As only the $R$-band magnitude was observed in the early epochs of SN 2006gy (the filled square), we cannot construct the bolometric LC at the early epochs; but we can constrain the rise time of the LC. Our calculations show that the rise time of the PISN model is too slow to be consistent with SN 2006gy. Although our PISN model does not have an H-rich envelope, the presence of the H-rich envelope could even slow down the brightening (e.g., Kawabata et al. 2009). Woosley et al. (2007) showed that the interaction between the pulsating core and the envelope can power the LC of SN 2006gy. As a similar mechanism, the interaction of an SN ejecta with its very dense circumstellar matter could convert the kinetic energy of ejecta directly to radiation energy and could also be the origin for a luminous SN like SN 2006gy.

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