THE MOST MASSIVE CORE-COLLAPSE SUPERNOVA PROGENITORS

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ABSTRACT

The discovery of the extremely luminous supernova SN 2006gy, possibly interpreted as a pair instability supernova, renewed the interest in very massive stars. We explore the evolution of these objects, which end their life as pair instability supernovae or as core-collapse supernovae with relatively massive iron cores, up to about 3 M\(_\odot\).

Subject headings: stars: evolution — supernovae: general
Online material: color figures

1. INTRODUCTION

The interest in the evolution of very massive stars (VMSs), with masses \(\geq 100 M_\odot\), has recently been revived by the discovery of SN 2006gy — the most luminous supernova ever recorded (Ofek et al. 2007; Smith et al. 2007). This object, having a luminosity of \(\sim 10^8\) times that of a typical core-collapse SN (CCSN), is probably the first evidence of a pair instability SN (PISN) (Woosley et al. 2007). PISN are massive stellar objects, whose evolutionary path brings their center into a region in thermodynamical phase space \((\rho \leq 10^6, T \geq 10^9)\), where thermal energy is converted into the production of electron-positron pairs, thus resulting in loss of pressure and hydrodynamic instability. This type of supernova was first suggested 40 years ago by Rakavy & Shaviv (1967) and Barkat et al. (1967), and since then several works were carried out (e.g., Fraley 1968; Ober et al. 1983; El Eid et al. 1983; Bond et al. 1984; Heger & Woosley 2002; Hirschi et al. 2004; Eldridge & Tout 2004; Nomoto et al. 2005); however, the overall interest in this topic has been relatively small, mainly due to lack of observational data.

It was originally believed that stars massive enough to produce PISN could only be found among population III stars with close to zero metallicity \((Z \leq 10^{-4})\), and hence only at very high redshift \((z \geq 15)\). More recently Scannapieco et al. (2005) discussed the detectability of PISN at redshift of \(z \leq 6\), arguing that metal enrichment is a local process, therefore metal-free star-forming pockets may be found at such low redshifts. Langer et al. (2007) introduced the effect of rotation into studying this question concluding that PISN could be produced by slow rotators of metallicity \(Z \leq 10^{-7}/3\) at a rate of one in every 1000 SN in the local universe. Furthermore, Smith et al. (2007) point out, that mass-loss rates in the local universe may be much lower than previously thought, so that massive stars might be left with enough mass to become PISN. This conclusion is also supported by Yungelson et al. (2008), who extensively discuss the mass-loss rates and fates of VMS. It is interesting to note that SN 2006gy took place in the nearby universe. Following the discovery of SN 2006gy, Umeda & Nomoto (2008) addressed the question of how much \(^{56}\)Ni can be produced in massive CCSN, while Heger & Woosley (2008) computed the detailed nucleosynthesis in these SNe.

The interest in VMS is further motivated by the discovery of ultraluminous X-ray sources (ULXs), which can be interpreted as mass-accreting intermediate-mass black holes (IMBHs) with mass \(\sim (10^2-10^5) M_\odot\). One of the possible scenarios for IMBH formation is by VMSs formed by stellar mergers in compact globular clusters (see, e.g., Yungelson et al. 2008 and references therein). In this context, Nakazato et al. (2006, 2007) studied the collapse of massive iron cores with \(M \geq 3 M_\odot\). In their first paper they treat the fate of stars of mass \(\geq 300 M_\odot\) which reach the photodisintegration temperature \((\sim 6 \times 10^9 K)\) after undergoing pair instability. The entropy per baryon of these models at photodisintegration is \(s > 16 k_B\) compared with the classical core-collapse SN with \(s \sim 1 k_B\). In the second paper they aim to bridge this entropy gap, corresponding to core masses of \((3-30) M_\odot\), but claim that there is a lack of systematic progenitor models for this range; hence they use synthetic initial models for their calculations. In this work we focus mostly on the mass range \(M \leq 80 M_\odot\) (He core mass \(M_{\text{He}} \leq 36 M_\odot\)) immediately below the range which enters the pair instability region, and present a systematic picture of the resulting CCSN progenitors.

2. METHOD

Since the mass-loss rates of stars in this range are highly uncertain (see, e.g., discussion by Yungelson et al. 2008), we avoid dealing with this question by following the example of Heger & Woosley (2002) and modeling the evolution of helium cores. Our helium core initial models are homogeneous polytropes composed entirely of helium and metals, with metallicity \(Z \approx 0.015\), in the mass range \((8-160) M_\odot\). The models were then evolved to the helium zero-age main sequence. In the following we refer to these models as “He N” where \(N\) is the mass of the model. For comparison we evolved also a few models of regular hydrogen stars, beginning from the zero-age main sequence (ZAMS). We will refer to these models as “MN” where \(N\) is the mass of the model. All our models have no mass loss. We argue that as long as the mass-loss rate is not so high that it will cut into the He core, the evolution after the main-sequence phase will be virtually independent of the fate of the hydrogen-rich envelope. We followed the evolution of each model until the star is either completely disrupted (for the PISN case) or Fe begins to photodisintegrate (for the CCSN case).

We followed the evolution using the Lagrangian one-dimensional Tycho evolutionary code version 6.92 (with some modifications), publicly available on the web (the code is described in Young & Arnett 2005). Convection is treated using the well known mixing length theory (MLT) with the Ledoux criterion. In the MLT formulation of Tycho, the value of the mixing length parameter fit to the Sun is \(\alpha_{\text{MLT}} \approx 2.1\) (Young & Arnett 2005), so we used a value of \(\alpha_{\text{MLT}} = 2\) in our calculations. The nuclear
Fig. 1.—Evolution of the central density and temperature. Each line is labeled “M” for stellar models and “He” for He-core models, followed by the mass of the model. The figure is divided into two panels for clarity: the left panel shows models that reach CC without reaching pair instability, and the right panel shows models reaching pair instability, subsequently experiencing pulsations (He48), complete disruption (He80), or direct collapse (He160). [See the electronic edition of the Journal for a color version of this figure.]
binding energy \(E\) is given when central temperature reaches 720 Ne mass fraction at the end of core He burning (Fig. 1):

\[ \text{Model} \quad M \quad M_{\text{He}} \quad M_{\text{CO}} \quad M_{\text{Si}} \quad M_{\text{He}} \quad X_{12} \quad X_{20} \quad \rho_{c} \quad T_{c} \quad S_{c} \quad Y_{e} \quad E_{\text{bin}} \quad \text{SN Type} \]

| Model | M | M_{\text{He}} | M_{\text{CO}} | M_{\text{Si}} | M_{\text{He}} | X_{12} | X_{20} | \rho_{c} | T_{c} | S_{c} | Y_{e} | E_{\text{bin}} | \text{SN Type} |
|-------|---|---------------|---------------|---------------|---------------|--------|--------|--------|------|-------|------|-------------|---------------|
| M20   | 20 | 6.1           | 2.71          | 2.05          | 1.44          | 0.200  | 0.003  | 5.9E+09 | 7.0  | 0.70  | 0.042 | 0.8         | CC            |
| M80   | 80 | 37.5          | 28.20         | 10.20         | 2.80          | 0.050  | 0.066  | 2.8E+08 | 7.0  | 1.64  | 0.045 | 3.9         | CC            |
| M100  | 100| 50.4          | 38.90         | 20.10         | 2.53          | 0.037  | 0.081  | 2.5E+08 | 7.0  | 1.72  | 0.045 | 4.0         | CC            |

**Notes.**—The columns represent for each model the total mass \(M\), He-core mass \(M_{\text{He}}\), CO-core mass \(M_{\text{CO}}\), Si-core mass \(M_{\text{Si}}\), Fe-core mass \(M_{\text{Fe}}\), and binding energy \(E_{\text{bin}}\). Masses are given in solar masses \(M_{\odot}\). Central density \(\rho_{c}\), central temperature \(T_{c}\), entropy per baryon \(S_{c}\), electron mole fraction \(Y_{e}\), and binding energy \(E_{\text{bin}}\) are given in units of 10^9 cm^-3, 10^9 K, and ergs per baryon, respectively. For the models reaching core collapse the data are given when central temperature reaches 7 \times 10^9 K, while for the models that disrupt after reaching pair instability the data are given at onset of instability.

The evolution is generally followed using the code’s hydrostatic mode. The pulsational pair instability models are treated as follows. When hydrodynamic instability is encountered, the code is switched to the hydrodynamic mode, and mass ejection is accounted for by removing outer zones having supersonic velocity in excess of the escape velocity. After mass ejection has died out, and the stellar core is already in contraction, the code is switched back to the hydrostatic mode to follow the interpulse period.

### 3. RESULTS

The He-core models we computed can be divided into four categories, according to their final fate, as can be seen in the central density and temperature plot (Fig. 1):

1. **CCSN.**—Models that reach core collapse (i.e., Fe photodisintegration) conditions without entering the region of pair instability. This is the fate of He cores with mass \(M \leq 36 M_{\odot}\), as can be seen for the models He8 and He36 in Figure 1.

2. **Pulsational PISN (PPI).**—Models that reach pair instability, collapse, and bounce due to the energy released by nuclear reactions, but the energy released is insufficient to disrupt the entire star, and thus a fraction of the star’s mass is emitted, and the star collapses back. This may happen several times, until the star has no more material to burn and reverse the collapse, and core-collapse conditions are reached. This occurs for models with...
Fig. 3.—Pre-SN composition of models M20, He8, M80, and He36. “Si” and “Fe” stand for the total of Si- and Fe-group elements, respectively. [See the electronic edition of the Journal for a color version of this figure.]
He-core mass in the range $36 < M \lesssim 54 M_\odot$, e.g., model He48 in Figure 1.

3. **PISN**.—Models that reach pair instability, collapse, and the energy released by nuclear reactions is high enough to disrupt the entire star. This occurs for models with He-core mass in the range $54 < M \lesssim 130 M_\odot$, e.g., model He80 in Figure 1.

4. **Pair instability core-collapse (PICC)**.—Models that reach pair instability, but the energy released is too low to reverse the collapse, and the star continues collapsing into the photodisintegration regime. This occurs for models with He-core mass in the range $M \lesssim 130 M_\odot$, e.g., model He160 in Figure 1.

The properties of our models at pre-SN are summarized in Table 1.

Figure 2 shows the density structure of the pre-SN, at the moment when the central temperature reaches $7 \times 10^9$ K. The two extreme models He8 and He36 are shown, as well as M80 which has a He-core mass similar to the He36 model, and M20—a typical CCSN progenitor. The composition of the same models is shown in Figure 3.

The size of the Fe, Si, and CO cores of our pre-SN models is shown in Figure 4 plotted against the size of the He core. A scaled-up view of the size of the Fe core (defined as the mass coordinate, where the electron mole fraction $Y_e < 0.49$) together with the central entropy per baryon for the same models is shown in Figure 5. Note that the size of the Fe core is slightly non-monotonic. The central entropy, is monotonic with mass, but slightly differs between He-core and stellar models.

From the above results it is notable that the He-core models behave similarly to the stellar models (compare, e.g., models He36 and M80, which has a He-core mass of $\approx 36 M_\odot$); however, some differences still exist (e.g., the central entropy in Fig. 5).

4. **CONCLUSIONS**

Our results are in general agreement with previously published results (e.g., Heger & Woosley 2002; Woosley et al. 2007; Umeda & Nomoto 2008). We focused on the heaviest models which do not encounter pair instability (CCSN) in the range (He8–He36). The outstanding novel features of these models are the following:

1. Relatively large Fe cores, up to about $3 M_\odot$, and a large amount (up to about $10 M_\odot$) of Si group elements.
2. Comparatively low central density and high central entropy.
3. A comparatively shallow density profile.

These differences might have a considerable impact on the behavior of these models during core collapse and on the outcome of the explosion, a question which we hope to address in the future.

Similar features are encountered for the lower mass part of the pulsational pair instability models (He38–He50). However, due to the numerical complexity of following the pulsations and the potential sensitivity of the results to the numerical treatment of convection, mass loss, and so on, further work is needed to ascertain the validity of the results for the pulsational models.

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