A database of spectral energy distributions of progenitors of core-collapse supernovae

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Received 2020 October 6; accepted 2021 February 10

Abstract This paper presents a database of the spectroscopic- and photometric-spectral energy distributions (spec-SEDs and phot-SEDs respectively) of the progenitors of core-collapse supernovae (CCSNe). Both binary- and single-star progenitors are included in the database. The database covers the initial metallicity (Z) range of 0.0001–0.03, mass range of 8–25 $M_\odot$, binary mass ratio range of 0–1, and orbital period range of 0.1–10,000 d. The low-resolution spec-SEDs and phot-SEDs of single- and binary-star CCSN progenitors are included in the database. These data can be used for studying the basic parameters, e.g., metallicity, age, and initial and final masses of CCSN progenitors. It can also be used for studying the effects of different factors on the determination of parameters of CCSN progenitors. When the database is utilized for fitting the SEDs of binary-star CCSN progenitors, it is strongly suggested to determine the metallicity and orbital period in advance, but this is not necessary for single-star progenitors.

Key words: (stars:) supernovae: general — astronomical databases — (stars:) binaries: general

1 INTRODUCTION

As the main kind of supernova (SN), a core-collapse supernova (CCSN), is an explosion that marks the death of a massive star. A CCSN is a singularly important phenomenon in the universe for two main reasons. First, CCSNe are principal drivers of cosmic chemical evolution. Most elements heavier than hydrogen (H) and helium (He), except those around the iron peak, were synthesized by CCSNe. Second, they are possibly related to the rapid neutron capture process (r-process), which produced many of the extremely heavy elements above atomic mass of approximately 70. CCSNe have observed kinetic energies of typically $\sim 10^{51}$ erg, and their integrated luminosities are usually 1%–10% of this value (Smartt 2009). Modeling the explosion of a CCSN has been a perennial challenge in theoretical astrophysics for decades as is understanding the progenitor of a CCSN.

The progenitor of a CCSN is fundamental for understanding CCSNe, in particular, for their explosions. However, the formation and properties of CCSN progenitors are still far from being well understood. It is well known that the minimum initial mass that can produce a CCSN is about 8 $M_\odot$, according to the direct detections of red supergiant progenitors and the most massive white dwarf (WD) progenitors. The maximum initial mass is less than about 25 $M_\odot$, because the majority of massive stars above 20 $M_\odot$ may collapse quietly to black holes and those explosions remain undetected. The progenitors of CCSNe have been widely studied, but the results are actually model dependent (Smartt 2009). The common image to form a CCSN progenitor is as follows. The H in stellar cores converts to He in stellar evolution. If a star is sufficiently massive, heavier elements such as carbon, oxygen, nickel, nitrogen, magnesium, silicon and iron (C, O, Ne, N, Mg, Si and Fe respectively) are subsequently produced in nuclear synthesis reactions. For stars more massive than 8 $M_\odot$, either an O-Ne-Mg core (Poelarends et al. 2008) or an Fe core (Woosley et al. 2002) will form eventually and would cause an SN explosion (Lisakov 2018).

Most studies of CCSN progenitors so far assume single-star models. For example, the nearest progenitor, SN 1987A, which was in the Large Magellanic Cloud (LMC), was shown to have evolved from a single star with initial mass in the range of 14–20 $M_\odot$. 

* The database and a phot-SED fitting code are available at github (https://github.com/zhongmuli/astrodata/tree/preCCSN_SED) and Zenodo (https://zenodo.org/record/4667934#.YG0IYLFDers).
Using detailed stellar evolutionary codes such as MESA (Paxton et al. 2011), many works evolved massive star models from the main sequence until core collapse (e.g., Lisakov et al. 2018). These works put forward a lot of studies on CCSN progenitors. However, single-star models ignore the observed fact that a lot of stars are in binaries. In fact, many SN progenitors are possibly binaries. For example, CCSN SN1993J needs a binary of 15+14 instead of single-star evolution, CCSN progenitors could differ a lot in mass, age, radius and composition from the main sequence until core collapse of 5.8 yr to explain the observed explosion of SN1993J. For example, CCSN SN1993J needs a binary of 15+14 instead of single-star evolution, CCSN progenitors could differ a lot in mass, age, radius and composition from the main sequence until core collapse of 5.8 yr to explain the observed explosion of SN1993J.

| Parameter | Range      | Step | Unit   | Note                  |
|-----------|------------|------|--------|-----------------------|
| \(Z\)    | 0.0001–0.03 | 8    | values | single star and binary star |
| \(M_0\)  | 8.0–25.0   | 0.1  | \(M_\odot\) | single star and binary star |
| \(q\)    | 0–1.0      | 0.1  | binary star |
| \(\log(P)\) | -1.0–4.0  | 0.5  | days  | binary star |
| \(e\)    | 0.3–0.7    | 0.4  | binary star |

\(q\), \(P\) and \(e\) are for binary stars only. Stellar mass \(M_0\) means the total main-sequence mass of a single or binary star. For binaries, the masses of primary and secondary components are calculated by \(M_1 = M_0/(1+q)\) and \(M_2 = q \times M_1\) respectively.

| Parameter or process | Symbol | Value | Note |
|----------------------|--------|-------|------|
| Reimers mass-loss coefficient | \(\eta\) | 0.5 | |
| helium star mass loss factor | | 1.0 | |
| CE efficiency parameter | \(\alpha\) | 3.0 | |
| binding energy factor for CE | \(\lambda\) | 0.5 | |
| spin-energy correction in CE | | | |
| tidal circularization | | | |
| using modified-Mestel cooling for WDs | | | |
| allowing velocity kick at BH formation | | | |
| taking NS/BH mass from Belczynski et al. (2002) | | | |
| maximum NS mass | \(m_{\text{ns}}\) | 3.0 | in \(M_\odot\) |
| dispersion in the Maxwellian for SN kick speed | \(\sigma\) | 190.0 | in km/s |
| wind velocity factor | \(\beta\) | 0.125 | \(\propto v_{\text{wind}}^2\) |
| wind accretion efficiency factor | \(\xi\) | 1.0 | |
| Bondi-Hoyle wind accretion factor | \(a_{\text{acc}}\) | 1.5 | |
| fraction of accreted matter retained in nova eruption | \(\epsilon_{\text{nov}}\) | 0.001 | |
| Eddington limit factor for mass transfer | eddfac | 10.0 | |
| angular momentum factor for mass lost during Roche lobe overflow | \(\gamma\) | -1.0 | |

Using detailed stellar evolutionary codes such as MESA (Paxton et al. 2011), many works evolved massive star models from the main sequence until core collapse (e.g., Lisakov et al. 2018). These works put forward a lot of studies on CCSN progenitors. However, single-star models ignore the observed fact that a lot of stars are in binaries. In fact, many SN progenitors are possibly binaries. For example, CCSN SN1993J needs a binary of 15+14 with an initial orbital period of 5.8 yr to explain the observed explosion of SN1993J. A potential surviving companion of Tycho Brahe’s type Ia SN from 1572 was found around the position of the explosion (Ruiz-Lapuente et al. 2004).

According to stellar evolution theory, binary stars evolve in a substantially different way from single stars if their components are not too far from each other. Binary interactions are therefore very important in stellar evolution (Podsiadlowski et al. 1992). Binary evolution affects both the population synthesis of a large amount of stars (Podsiadlowski et al. 2002; Belczynski et al. 2008; Han et al. 2007; Li & Han 2008; Zhang & Li 2006; Eldridge et al. 2017; Farrell et al. 2020) and the detailed models of a small number of stars. If binary evolution is taken instead of single-star evolution, CCSN progenitors could differ a lot in mass, age, radius and composition from the main sequence until core collapse of 5.8 yr to explain the observed explosion of SN1993J. If binary evolution is taken instead of single-star evolution, CCSN progenitors could differ a lot in mass, age, radius and composition from the main sequence until core collapse of 5.8 yr to explain the observed explosion of SN1993J.
only two metallicities were considered and it is not enough for many studies of CCSN progenitors, in particular SED studies.

Besides binarity, stellar rotation and magnetic fields were also not considered in most CCSN progenitor studies, although they have some effects on the formation and properties of progenitors (e.g., Heger et al. 2000; Meynet & Maeder 2007; Woosley & Janka 2005; Langer 2012). In fact, there is still a long way to go, because the effect of stellar rotation and magnetic field remains very uncertain (e.g., Powell & Müller 2020).

In the studies of CCSNe, there have been a few good algorithms, e.g., Supernova Identification (SNID). Such codes can be utilized to identify the type of an SN spectrum and to determine its redshift and age (Blondin & Tonry 2007). However, there is no comprehensive SED database to determine the properties of different kinds of CCSN progenitors yet. This hampers many studies, e.g., the identification of the CCSN progenitor on pre-explosion images. This work therefore aims to build a database of the photometric- and spectroscopic- spectral energy distributions (phot- and spec-SEDs) of CCSN progenitors. Both photo-SEDs and spec-SEDs are examined here because they are the main approaches to estimate the properties of CCSN progenitors. This is the first attempt to give the predicted SEDs of CCSN progenitors.

The structure of paper is as follows: in Section 2, we introduce the parameter ranges of stars and the calculation of stellar evolution. Then in Section 3, we introduce the stellar property parameters included in our database. Sections 4 and 5 present the Spec-SEDs and Phot-SEDs of CCSN progenitors respectively. Next, in Section 6, we apply the database to some mock progenitors with phot-SEDs. Finally, we conclude this work in Section 7.

### Table 3 Comparison of the final mass and age of CCSN progenitors of this work to two previous works (Lisakov 2018; Dessart et al. 2010).

| $M_{\text{final}}$ | $M_{\text{BSE}}$ | $M_{\text{MESA}}$ | $M_{\text{Woosley}}$ | $\text{Age}_{\text{BSE}}$ | $\text{Age}_{\text{MESA}}$ |
|-------------------|-----------------|-----------------|-------------------|-----------------|-----------------|
| 13.0              | 11.5            | 11.1            | 12.64             | 17.7            | 15.3            |
| 15.0              | 10.0            | 11.9            | 12.64             | 14.3            | 12.5            |
| 17.0              | 9.9             | 14.2            | 12.0              | 10.5            | 9.7             |
| 19.0              | 10.1            | 13.6            | 10.5              | 9.4             |                 |
| 21.0              | 7.3             | 8.6             | 9.3               | 8.5             |                 |
| 23.0              | 8.1             | 8.1             | 8.5               | 7.7             |                 |
| 25.0              | 8.3             | 8.6             | 12.53             | 7.8             |                 |

Subscript ‘BSE’ corresponds to the results of this work, while ‘MESA’ and ‘Woosley’ signify the results that are calculated via MESA (Paxton et al. 2011) and Woosley et al. (2002) codes, respectively. All models have the metallicity of $Z = 0.02$. $M_{\text{final}}$ is initial main sequence mass.

### 2 STELLAR PARAMETER RANGES AND EVOLUTION COMPUTATIONS

#### 2.1 Parameter Ranges

This work aims to supply an SED database with a large parameter coverage and reasonable resolution, so the parameter ranges are wider than most previous works. In detail, stellar metallicity ($Z$) covers a range of 0.0001–0.03. Stars from metal-poor to metal-rich kinds are included. The zero-age main-sequence mass range of single stars is set to 8–25 $M_\odot$ because most CCSN progenitors have main-sequence masses in this range. This range is similar to some theoretical studies (e.g., Straniero 2018) but larger than some observational results (8.5–16.5 $M_\odot$, e.g., Smartt 2009 and references therein). The same range is set to the total mass ($M_1 + M_2$) of two binary components. The range of the mass ratio of secondary to primary of binaries, $q$, is set to 0–1. The orbital period ($P$) of a binary changes from 0.1 to 10$^4$ d. In fact, within the current age of the universe, the evolution of binaries with periods longer than 10$^4$ d is similar to the counterparts with a period of 10$^4$ d. The intervals of $M_1$, $q$ and $\log P$ of main-sequence stars are set to 0.1, 0.1 and 0.5, respectively. Two values (0.3 and 0.7) are chosen for the eccentricity ($e$) of binary stars, as previous studies (e.g., Hurley et al. 2002) have demonstrated that $e$ affects the final results somewhat slightly. Although the evolution of massive stars is sensitive to metallicity, binarity, rotation and possibly magnetic fields, rotation and magnetic field are not taken into account in this work because of their huge uncertainties. Table 1 lists the parameter ranges and steps of zero-age main sequence stars, which are taken by this work.

Note that the mass range of this work is similar to most previous studies and findings. For example, Smartt (2009) investigates a mass range of 8–25 $M_\odot$. Lisakov et al. (2018) take 12, 25 and 27 $M_\odot$ in their work. Dessart et al. (2010) perform some radiation-hydrodynamic simulations and indicate that the progenitor main-sequence masses are less than ~ 20 $M_\odot$, and the range of 25–30 $M_\odot$ is not supported by the narrow width of OI 6303–6363 Å in Type II-P SNe with nebular spectra. Langer (2012) reported the likely minimum initial mass range of massive stars at solar metallicity of 8–12 $M_\odot$, according to Poelarends et al. (2008). In close binaries, this limit depends on other initial system parameters such as metallicity and orbital period. The mass limit at solar metallicity can be as high as 15 $M_\odot$ (Wellstein et al. 2001).
2.2 Calculation of Stellar Evolution and Progenitor Properties

This work models the parameters of CCSN progenitors with a reasonable resolution, via a rapid population-synthesis code, BSE (Hurley et al. 2000, 2002). It takes some fitting formulae based on the reliable stellar evolutionary tracks of Pols et al. (1998). In addition to all aspects of single-star evolution, binary interactions including mass transfer, mass accretion, common-envelope (CE) evolution, collisions, SN kicks and angular momentum loss mechanisms have been taken into account by this code, and the calculation result is similar to some detailed stellar evolution codes (Langer 2012). This code is fast for modeling the population of a large number of single or binary stars. It is widely utilized in many stellar population synthesis studies, e.g., Zhang & Li (2006); Han et al. (2007); Li et al. (2012, 2013, 2016); Luo & Li (2018); Li & Mao (2018). It has also been used by some previous works, e.g., Eldridge & Tout (2004) and Eldridge et al. (2008), to reproduce the observed trends such as the distribution of well-studied SN progenitors in the metallicity versus initial mass plane, and the ratio of the Type Ib/c SN rate to the Type II SN rate. The code makes it possible to cover large ranges of parameters in the studies of CCSN progenitors. Although there are small uncertainties ($\leq 5$ per cent) in the luminosity, radius and core mass compared to detailed stellar evolution codes, the accuracy is enough for most SED studies of CCSN progenitors, as the uncertainties in phot-SEDs of distant CCSN progenitors are usually larger.

When evolving stars, some default values of BSE code are taken for the input parameters, because they have been checked by the developer and are widely applied in different works. They are listed in Table 2 to help the readers to understand the physical processes in the evolution of CCSN progenitors. Note that there is an important difference between single stars and close binary components. Close binary components undergo mass transfer following Roche lobe overflow but single stars do not. Mass transfer can occur between two binary components including different types. WDs are the only degenerate objects able to fill their Roche lobes for a significant amount of time without breaking up. Thus dynamical mass transfer from a WD can occur in binary evolution. Mass accretion onto degenerate objects is important both during Roche lobe overflow and when material is accreted from the wind of the companion. Accretion is assumed to be restricted by the Eddington limit. Two binary components can merge to a single remnant in some cases. Besides nondegenerate stars and WDs, neutron stars (NSs) and black holes (BHs) can also merge. This will increase the mass and possibly change the type of the remnants. The angular momentum loss that is caused by both gravitational radiation and magnetic braking is considered by the BSE code. One can read Tout et al. (1997); Pols et al. (1998); Hurley et al. (2002) for more details about the treatment of stellar evolutionary processes.

The progenitors of CCSNe are massive stars that evolve very fast. A C-O core or Fe core is finally formed and its mass grows with stellar evolution, up to the effective Chandrasekhar mass ($\geq$ about $1.26 M_\odot$). Once the core attains this critical mass, unstable gravitational collapse and explosion ensues. This work gives the properties of CCSN progenitors at the moment of the explosion. The CCSN progenitors are found by comparing

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**Fig. 1** Final mass as a function of initial mass for solar-metallicity CCSN progenitors. Green points are for single-star progenitors, while red points and blue circles for the primary and secondary components of binary-star progenitors respectively. Gray triangles signify the total mass of binary-star progenitors.

**Fig. 2** Age as a function of initial mass for solar-metallicity CCSN progenitors. Colors have the same meanings as in Fig. 1.
Fig. 3 Distribution of CCSN progenitors in the plane of gravity (log $g$) versus effective temperature ($T_{\text{eff}}$). $T_{\text{eff}}$ is in K. Red filled and black open circles are for the primaries and secondaries of binary-star CCSN progenitors, respectively.

the change of star type and the mass of stellar core, which is similar to the method of Eldridge et al. (2008). The phot- and spec-SEDs, age, mass, effective temperature, luminosity, gravitational acceleration and radius are given for each progenitor. If the progenitor is a binary, orbital period and eccentricity are also given.

A standard and widely used stellar spectral library, BaSeL 3.1 (Lejeune et al. 1997, 1998), is utilized for
Fig. 4 Contributions of two components to the combined SED of a binary-star CCSN progenitor. Two components have solar metallicity, and initial masses of 11.54 $M_\odot$ and 3.46 $M_\odot$. Green and black lines are for the SEDs of primary and secondary components respectively, while red line is for the combined SED.

transforming the stellar evolutionary parameters to spec-SEDs when calculating the SEDs of CCSN progenitors. The SEDs cover a large wavelength range from ultraviolet (UV) to medium infrared (MIR), which is suitable for most multi-band studies. This library is a comprehensive hybrid library of synthetic stellar spectra based on three original grids of model atmosphere spectra. It covers the largest possible ranges in stellar parameters ($T_{\text{eff}}$, $\log g$ and [M/H]) and provides flux spectra with useful resolution on a uniform grid of wavelengths. The standard library has been calibrated and its consistency has been tested carefully. In particular, the library spectra were successfully reproduced the empirical color temperature relations. After the calculation of spec-SEDs, the phot-SEDs are calculated from spec-SEDs, by taking the AB photometry system. All magnitudes of progenitors are calibrated referencing the data of Vega.

3 PROPERTIES OF CCSN PROGENITORS

The properties are given with the same format for single- and binary-star progenitors. A single-star progenitor is regarded as a binary-star progenitor with a zero-mass component. The case of single-star progenitors is relatively simple, but it becomes much more complicated when including binary-star evolution. The likely important role of binary-star evolution in the formation of SN progenitors remains to be thoroughly explored (see, e.g., Cantiello et al. 2007). Overall, these complications make the final mass, radius and age of the CCSN progenitors uncertain (Dessart et al. 2010). For a general use purpose, the age, mass, effective temperature, luminosity, gravitational acceleration, radius and star type of progenitors are

Fig. 5 Spec-SEDs of example CCSN progenitors. The metallicity $Z$ is 0.001. Solid and dashed lines are for 9.1 $M_\odot$ and 20 $M_\odot$ models respectively; “single” corresponds to single-star progenitors, while orbital period numbers signify binary-star progenitors. Blue, green, red and purple lines are for orbital periods of 3162, 100, 10 and 10000 d respectively, while black lines are for single-star progenitors.

Fig. 6 Similar to Fig. 5, but for a solar metallicity of $Z = 0.02$.

Fig. 7 Similar to Fig. 5, but for a metallicity of $Z = 0.03$. 
Table 4: CCSN Progenitor Models for Figs. 9 and 10

| No. | $m_1$ | $m_2$ | $P$   | $e$ | No. | $m_1$ | $m_2$ | $P$   | $e$ |
|-----|------|------|------|----|-----|------|------|------|----|
| 1   | 8.18 | 0.82 | 3162 | 0.3| 1   | 8.18 | 0.82 | 10000 | 0.3|
| 2   | 8.18 | 0.82 | 10000| 0.3| 2   | 16.36| 1.64 | 10000 | 0.3|
| 3   | 7.50 | 1.50 | 10000| 0.3| 3   | 19.09| 1.91 | 3162  | 0.3|
| 4   | 10.91| 1.09 | 3162  | 0.3| 4   | 17.50| 3.50 | 3162  | 0.3|
| 5   | 13.64| 1.36 | 3162  | 0.3| 5   | 20.00| 2.00 | 3162  | 0.3|
| 6   | 16.36| 1.64 | 3     | 0.7| 6   | 8.57 | 3.43 | 3162  | 0.3|
| 7   | 16.36| 1.64 | 3162  | 0.3| 7   | 9.23 | 2.77 | 3162  | 0.3|
| 8   | 10.91| 1.09 | 10000 | 0.3| 8   | 10.00| 2.00 | 3162  | 0.3|
| 9   | 10.00| 2.00 | 3162  | 0.3| 9   | 9.23 | 2.77 | 3162  | 0.3|
| 10  | 9.23 | 2.77 | 10000 | 0.3| 10  | 13.64| 1.36 | 3162  | 0.3|
| 11  | 13.64| 1.36 | 3162  | 0.3| 11  | 10.00| 2.00 | 10000 | 0.3|
| 12  | 12.50| 2.50 | 10000 | 0.3| 12  | 13.64| 1.36 | 10000 | 0.3|

“No.” means the line number in two figures. $m_1$ and $m_2$ are in $M_\odot$, and $P$ is in days.

Fig. 8 Example phot-SEDs of single-star CCSN progenitors. Black, red, green, blue, cyan, purple, yellow and orange colors are for $Z = 0.0001$, 0.0003, 0.001, 0.004, 0.008, 0.01, 0.02 and 0.03, respectively. Lines with the same color but different shapes are for various masses.

Fig. 9 Example phot-SEDs of binary-star CCSN progenitors with metallicities of 0.0001 and 0.03. Gray area indicates the range of all phot-SEDs of all binary-star progenitors in the database. The detailed model parameters of these CCSN progenitors are listed in Table 4.

Fig. 10 Similar to Fig. 9, but for a metallicity of $Z = 0.02$.

Fig. 11 Comparison of input ($m_{\text{mock}}$) and reproduced ($m_{\text{fit}}$) masses of single-star progenitors in phot-SED fitting. Different symbols correspond to different metallicities.
Fig. 12 Comparison of input ($m_{\text{mock}}$) and reproduced ($m_{\text{fit}}$) masses of binary-star progenitors in phot-SED fitting. The result is for the case of free metallicity and orbital period. Filled circles, open circles and pentagrams are for primary mass, secondary mass and total mass respectively.

Fig. 13 Similar to Fig. 11, but for binary-star progenitors with known metallicity and orbital period.

Fig. 14 Similar to Fig. 5, but for another stellar evolution calculation (Spera et al. 2019). Solid and dashed lines are for total stellar masses of 9.1 and 20 $M_\odot$ respectively.

Figures 1–3 display the distribution of CCSN progenitors in various spaces. Figure 1 depicts the progenitor distribution in the initial mass versus final mass plane. We clearly observe some difference between single- and binary-star progenitors. The final mass of a single-star progenitor is lower than about 12 $M_\odot$, but that of a binary-star progenitor can be as large as 24 $M_\odot$ because of the mass transfer between binary components. Note that different stellar evolution codes usually give different final masses. The difference among the results can be as large as 6 $M_\odot$ (see the comparison of results from, e.g., Heger et al. 2000; Lisakov 2018; Lisakov et al. 2018).

Figure 2 features the progenitor distribution in the age versus initial mass plane. We observe that the age of single-star progenitors decreases with increasing initial mass. Meanwhile, the case of binary-star progenitor is much more complicated. In particular, some binary-star progenitors have significantly older ages than those single-star progenitors. The reason is that a long time is needed for the mass exchange of these binary-star progenitors.

Figure 3 depicts the progenitor distribution in the gravity versus effective temperature plane. We see that many primaries of binary-star CCSN progenitors are located in the high-temperature ($T_{\text{eff}} > 10^5$ K) area but there are much less secondary components in this region. This implies that primaries contribute more to the combined SEDs at short wavelengths, which is verified by the example in Figure 4. That figure gives the contributions of two components of binary-star progenitors to the combined SED. From the figure we also find that both components of binary-star progenitors contribute to the combined SEDs at long-wavelengths.

When comparing the final masses of CCSN progenitors to the results of Lisakov (2018) and Dessart et al. ...
(2010), the results of this work (calculated via BSE) are found to be consistent with those calculated via MESA code (Paxton et al. 2011). Table 3 lists the results of different works.

4 SPEC-SEDS

This section presents the spec-SEDS of both single- and binary-star CCSN progenitors. Because the database is as large as 1.4 GB, only some examples are included here. One can see Figures 5–7 for the spec-SEDS of a few example progenitors with metallicities of 0.001, 0.02 (solar metallicity) and 0.03, and total main-sequence masses of 9.1 $M_\odot$ (solid lines) and 20 $M_\odot$ (dashed lines). We ascertain that there is an obvious difference between the SEDs of single- and binary-star progenitors, even though they have the same metallicity and total mass. This suggests that different results will be possibly obtained when fitting to the observed SEDs using single- and binary-star progenitor models.

5 PHOT-SEDS

This section showcases the phot-SEDS of CCSN progenitors. Such SEDs are usually more useful for the studies of CCSN progenitors. All phot-SEDS are calculated from the spec-SEDS. The AB system is adopted for the purpose of wide applications. As a result, the AB magnitudes in FUV, NUV, u, g, r, i, z, J, H, Ks, W1, W2 and W3 bands are calculated. This makes it possible to study the phot-SEDS of CCSN progenitors in a wide wavelength range. Figures 8–10 feature some examples of the phot-SEDS of single- and binary-star progenitors. Figure 8 depicts the phot-SEDS of single-star progenitors, for eight metallicities from 0.0001 to 0.03. It is confirmed that single-star progenitors with various masses and metallicities usually have different phot-SED shapes. Some massive progenitors with metallicity poorer than 0.001 have UV-upturn phot-SEDS. However, there is obvious overlap for the phot-SEDS of single-star progenitors. This implies that the metallicity and main-sequence mass of such progenitors can be determined via fitting to the observed SEDs, but the uncertainties of the results of some progenitors will be possibly large. This agrees with previous studies on SNe such as SN 1987A. Similarly, Figures 9 and 10 display the phot-SEDS of some example binary-star CCSN progenitors.

6 APPLICATION OF SED DATABASE TO MOCK PROGENITORS

This section applies the database to some mock CCSN progenitors. The phot-SEDS of mock progenitors are fitted using the database. Each phot-SED consists of the magnitudes in FUV, NUV, u, g, r, i, z, J, H, Ks, W1, W2 and W3 bands. It is found that the main-sequence mass, age and metallicity of most single-star progenitors can be reproduced as a whole, although a few progenitors are not reproduced well because of the metallicity and mass degeneracy. As an example, Figure 11 features a comparison of input and reproduced masses of single-star progenitors.

However, the main-sequence masses of most binary-star progenitors are not reproduced correctly, if all parameters are free in the SED fitting (Fig. 12). The fitted main-sequence masses of most binary-star progenitors are much lower than the real values. This is caused by the degeneracy among mass, metallicity and orbital period. In order to find a reliable method for determining the main-sequence masses of binary-star progenitors, the cases of fixed metallicity or fixed period are tested, but the uncertainties in results are still large. Finally, the case of fixed metallicity and period gives satisfactory results (see Fig. 13). This means that if one wants to determine the masses of binary-star progenitors reliably, the metallicity and orbital period (initial or final values) are suggested to be determined in advance.

7 CONCLUSION

This paper presents a new database of SEDs of the single- and binary-star CCSN progenitors. Both the phot- and spec-SEDS of progenitors are included in the database. The database covers wide ranges of metallicity (0.0001–0.03), main-sequence mass (8–25 $M_\odot$), component mass ratio (0–1), binary period (0.1–10^4 d) and two eccentricities (0.3 and 0.7). It is then applied to the phot-SEDS of some mock CCSN progenitors. Our investigation leads to the following conclusions:

– The database of spec- and phot-SEDS of CCSN progenitors can be used for the studies of progenitor properties, and the difference between binary- and single-star progenitors. The results are consistent with those calculated via MESA code (Paxton et al. 2011), but the database is model dependent. Thus it is better for statistical studies such as population synthesis. It can be potentially applied for the identification of CCSN progenitors in large surveys. Stellar evolutionary code can affect the results, but the relative results are usually similar. For example, when we utilize the code of Spera et al. (2019) to calculate the SEDs instead of Hurley et al. (2002), similar results are generated (see Fig. 14).

– Binary-star CCSN progenitors have much more complicated parameter spaces than single-star pro-
It leads to much larger uncertainties in the determination of progenitor properties including component masses, total mass, metallicity and period.

- Binaries with component masses less massive than $8 \, M_\odot$ can form CCSN progenitors, although single stars less massive than this value cannot lead to CCSNe.

- When the SED database is used for determining the properties of CCSN progenitors, whether the progenitor is a single or binary star significantly affects the resulting accuracy. If progenitors are single stars, the initial and final mass can be determined well for most progenitors via phot-SEDs from $FUV$ to $W3$ bands. However, the results will be not reliable for binary-star progenitors, if metallicity, mass and period are set as free parameters of fit. In order to get reliable results, the metallicity and binary period (initial or final periods) need to be measured by relying on other methods. If these two parameters are known, the masses of binary components can be determined well via SED fitting.

Acknowledgements

The authors thank Prof. Xiaofeng Wang for suggestions and Dr. Jicheng Zhang for discussions. This work has been supported by the National Natural Science Foundation of China (Grant No. 11863002), Sino-German Cooperation Project (Grant No. GZ 1284) and Yunnan Academician Workstation of Wang Jingxiu (Grant No. 202005AF150025).

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