Excavating the Explosion and Progenitor Properties of Type IIP Supernovae via Modeling of their Optical Light Curves

Wilson Ricks and Vikram V. Dwarkadas

Dept. of Astronomy and Astrophysics, University of Chicago, 5640 S. Ellis Ave., Chicago, IL 60637, USA; vikram@astro.uchicago.edu

Received 2018 November 28; revised 2019 June 5; accepted 2019 June 6; published 2019 July 25

Abstract

The progenitors of Type IIP supernovae (SNe) are known to be red supergiants, but their properties are not well determined. We employ hydrodynamical modeling to investigate the explosion characteristics of eight Type IIP SNe and the properties of their progenitor stars. We create evolutionary models using the MESA stellar evolution code, explode these models, and simulate the optical light curves using the STELLA code. We fit the optical light curves, $\text{Fe} \ II \ 5169$ Å velocity, and photospheric velocity to the observational data. Recent research has suggested that the progenitors of Type IIP SNe have a zero-age main-sequence (ZAMS) mass not exceeding $\sim 18 \, M_\odot$. Our fits give a progenitor ZAMS mass of $\leq 18 \, M_\odot$ for seven of the SNe. Where previous progenitor mass estimates exist from various sources, such as hydrodynamical modeling, multiwavelength observations, or semi-analytic calculations, our modeling generally tends toward the lower-mass values. This result is in contrast to results from previous hydrodynamical modeling but consistent with those obtained using general-relativistic radiation-hydrodynamical codes. We do find that one event, SN 2015ba, has a progenitor whose mass is closer to $24 \, M_\odot$, although we are unable to fit it well. We also derive the amount of $^{56}\text{Ni}$ required to reproduce the tail of the light curve and find values generally larger than previous estimates. Overall, we find that it is difficult to characterize the explosion by a single parameter, and that a range of parameters is needed.

Key words: hydrodynamics – methods: numerical – radiation mechanisms: general – radiative transfer – stars: evolution – supernovae: general

1. Introduction

Supernovae (SNe) are divided into various types based on their spectra and sometimes their light curves (Turatto 2003). Type II SNe show H lines in their spectra and are thought to be all core-collapse, i.e., those that arise from the explosion of massive stars $\gtrsim 8 \, M_\odot$. Type I SNe do not show H lines in their spectra. Of the SNe that comprise this category, Type Ia SNe are presumed to arise from white dwarfs in binary systems (Hillebrandt et al. 2013). Type Ib and Ic SNe do not show H (Ib) and He (Ic) lines in their spectra. The lack of H and He envelopes had early on pointed to high-mass Wolf–Rayet (W-R) star progenitors (Gaskell et al. 1986), which are stripped of their H and He envelopes. It is also possible that they may arise from somewhat lower-mass stars in a binary system, where the companion star is responsible for mass being stripped off the progenitor. In either case, it is clear that they arise from the core collapse of a massive star.

Type IIP SNe, which show a plateau in their optical light curves, are the most common type of core-collapse SN (Smartt et al. 2009; Eldridge et al. 2013). Observations show that they comprise almost 50% of total core-collapse SNe. The progenitors of Type IIP SNe are well established as being red supergiant (RSG) stars (see, for example, Smartt 2009). The RSGs are post-main-sequence massive stars that have finished burning H and are in the He-burning phase. Stars up to about $30 \, M_\odot$ will end their lives as RSGs, giving rise to IIP or perhaps IIL (which show a linear drop in the light curve, in contrast to the plateau seen in the IIPs) SNe (Ekström et al. 2013). Stars with an initial mass above $30 \, M_\odot$ but lower than about $40 \, M_\odot$ may pass through an RSG phase but end their lives as W-R stars. The range may vary somewhat depending on the actual mass-loss rates of these stars throughout their evolution, as well as factors like rotation and magnetic fields, which have only recently been taken into consideration.

The fates of massive stars and the progenitors of the various types of SNe are an active area of research (Gal-Yam et al. 2007). Even though several thousand SNe are known, the relationship between the massive stars that core-collapse and the type of SNe that they go on to form is not well established. In this context, it may seem that the IIPs are in a special position, as their progenitors are clearly RSGs, and the SNe themselves are visibly identifiable via the plateau in their light curves. But the parameters that determine the properties of the light curve, such as its shape; the duration and luminosity of the plateau; the emission beyond the plateau; and their relation to the stellar parameters, especially the zero-age main-sequence (ZAMS) stellar mass, and the SN explosion parameters, such as the explosion energy and $^{56}\text{Ni}$ mass, are not well understood (Faran et al. 2014; Nakar et al. 2016).

Early observations of SN progenitors suggested progenitor masses of Type IIP SNe generally below $20 \, M_\odot$ (Hendry et al. 2006; Li et al. 2006, 2007), leading to suggestions that Type IIP SNe arose from progenitors of $< 20 \, M_\odot$ (Li et al. 2007). This was better quantified by Smartt (2009), who found, in their study of optically identified Type IIP SN progenitors, that IIP progenitors did not seem to exceed $16.5 \pm 1.5 \, M_\odot$. This has come to be known as the RSG problem. Yoon & Cantiello (2010) found that pulsationally driven superwinds could change the evolution of a star of initial mass $> 19 \, M_\odot$, causing it to become a Ib or IIn SN, or perhaps even a In, but no longer a IIP. Ekström et al. (2012) suggested another possibility: that the outer layers could exceed the Eddington limit, resulting in enhanced mass loss. Whatever the reason, Georgy et al. (2012) showed that with an enhanced mass-loss rate, rotating stars above $16.8 \, M_\odot$ and nonrotating stars above $19 \, M_\odot$ would end
their lives as W-R stars rather than RSGs and would not give rise to IIP SNe. Horiuchi et al. (2014) and Kochanek (2015) suggested that the RSG problem may be understood if stars above a certain mass limit collapse directly to black holes, and that the value of the compactness parameter may determine the boundary between successful and failed explosions. There have also been suggestions that dust extinction (Walmswell & Eldridge 2012) or the increasing bolometric correction (Davies & Beasor 2018) have not been properly taken into account and could help to mitigate the problem.

Dwarkadas (2014) showed, from an analysis of X-ray light curves of SNe, that the lack of X-ray-bright Type IIPs seemed to indicate an upper mass-loss limit, and thereby an upper mass limit, of about 19 $M_\odot$ for IIP progenitors. Smartt (2015), using a larger sample, reassessed the optical data and concluded that the problem was even more severe, that observed populations of SNe in the local universe are not produced by stars $>18 M_\odot$, and that most stars with initial masses above this value would collapse directly to black holes without leaving a visible SN. The latter assumption has also received some support from theoretical calculations of stellar collapse by Sukhbold et al. (2016), who found that only about 10% of SNe arise from stars with ZAMS masses $>20 M_\odot$. Observations of an RSG in NGC 6946 that faded away over a decade, with no indication of an SN explosion or debris (Adams et al. 2017), have provided further impetus to this line of reasoning.

A very large data set of confirmed progenitor masses of SNe is needed to decipher how massive stars end their lives, if (and whether) they core-collapse to an SN or go directly to black holes, and what type of SN results from this. Unfortunately, confirming progenitor masses is a very difficult task. Several efforts are underway to optically detect SN progenitors (Smartt et al. 2009; Smartt 2015; Elias-Rosa 2016; Maund 2017; Van Dyk 2017). While direct optical identification of progenitors continues, it is a slow and time-consuming process that depends on the availability of high-resolution imaging in the past.

There also exist indirect ways of learning more about the SN explosion and progenitor. One of these is by modeling the optical light curves of the SN starting from the evolution of the pre-SN star. Type IIP SNe are characterized by a distinct and long-lasting (several months) plateau in their optical light curve. Parameters involved in simulating the light curve, such as the initial rise, plateau luminosity, duration of the plateau, and slope of the tail, can provide information on various explosion parameters, such as the $^{56}$Ni mass, explosion energy, and presence of circumstellar material (CSM) around the SN. The evolution of the star, its collapse to form an SN, and the accurate modeling of the light curve can provide a measure of the initial ZAMS mass. Hitherto, this has always been a time-consuming and computationally expensive endeavor, requiring several steps, as follows.

1. Modeling the evolution of the high-mass star (that gave rise to the SN) up to core collapse using a stellar evolution code.
2. Modeling the explosion of the star to give rise to an SN.
3. Using a radiation hydrodynamics code to model the SN light curve.
4. Reiterating steps 1–3 until a good model fit is obtained.

Recent advances have, however, made such calculations more feasible. The release and continued development of the MESA code (Paxton et al. 2011, 2013, 2015, 2018) has provided astronomers with access to a modern stellar evolution code that includes a variety of physics and the ability to construct models for stars of most initial masses and metallicities, taking various mass-loss prescriptions into account. The SNEC code (Morozova et al. 2015) was made available to model the explosion of SNe and calculate the resulting light curve in various bands. The combination of MESA and SNEC has been used by several authors (Morozova et al. 2016; Das & Ray 2017; Patnaude et al. 2017). More recently, Paxton et al. (2018) provided a complete recipe to accomplish this task by combining the MESA code with a reduced version of the STELLA code (Blinnikov et al. 1998, 2006; Blinnikov & Sorokina 2004), which allows for all of the steps necessary in calculating the light curves to be completed entirely within the MESA framework. This development allows for the entire process, from the initiation of the stellar model to the production of the optical light curve, to be accomplished in less than a day. As is to be expected, MESA cannot deal with each step in all its complexity. In particular, it does not attempt to model the microphysics of the SN explosion itself, which would be a huge task. Instead, the model star is exploded through a mechanism that artificially imparts the required energy and some other parameters, thus leaving some freedom in how these are calculated. We note that this is not unusual—a similar technique is utilized in the SNEC code, for example. The method used in MESA is further described in Section 2.

In this paper, our goal is to explore the properties of recent Type IIP SN explosions; evaluate both the explosion characteristics and the properties of the exploded star; study the relationships, if any, between the factors that determine the shape and luminosity of the IIP light curve and the properties of the SN explosion; and unearth the progenitor mass. In order to accomplish this, we use the combination of MESA and STELLA codes to simulate the light curves of several Type IIP SNe and compare to the observations. A good fit to both the light curves and photospheric velocities allows us to constrain the explosion and stellar properties and thereby determine the progenitor mass. In Section 2 we outline the basic procedure used in calculating the light curves with MESA and STELLA. Section 3 displays the application of this technique to match the observed light curves and photospheric velocities for a set of Type IIP SNe. Each SN is discussed in detail. Section 4 displays the relationships between various parameters, including stellar mass, $^{56}$Ni mass, and explosion energy from our work and compares them to those in the literature. Finally, Section 5 summarizes our research, discusses further prospects, and revisits the conclusions for the progenitors of Type IIP SNe.

2. Using MESA and STELLA to Compute Light Curves

MESA is a state-of-the-art, one-dimensional, modular, open-source suite for stellar evolution (Paxton et al. 2011, 2013, 2015, 2018). A variety of physics modules are included, which allow for modeling of single stars, as well as those in binary systems. The suite of tools has recently been extended (Paxton et al. 2018) to include the explosion of massive stars and the modeling of SN light curves. In the present work, done using the 10398 release of MESA, the code is used to model the evolution of high-mass stars ($>8 M_\odot$) from the protostellar phase until they form an Fe core, at which point they eventually core-collapse as SNe. MESA then simulates the SN explosion by removing the proto–neutron star, allowing the
model to continue infall until its inner boundary reaches 200 km, and then injecting a specified amount of energy into a thin layer near this inner boundary to induce the explosion. Because the explosion is not explicitly modeled, the user must also specify the total mass of synthesized $^{56}$Ni, whose value is adjusted in our calculations such that the simulated light curves match the observed ones. MESA handles the SN shock propagation until just before breakout, at which point STELLA takes over.

 STELLA models the breakout itself and the shock interaction with CSM through the nebular phase. It computes the primary SN observables over this period. The limited version of STELLA packaged with MESA includes 40–200 frequency groups, which is adequate to produce light curves but not SN spectra. Therefore, in this paper, we have chosen to compare the models to observations of the light curves. STELLA provides not only the total bolometric light curve but also light curves in the $U$, $B$, $V$, $R$, and $I$ passbands (Bessell 2005). As pointed out in Paxton et al. (2018), comparing the simulated light curves with the observational ones using the $UBVRI$ filters and the resulting (quasi-)bolometric light curves can result in a degeneracy in the progenitor mass. This degeneracy can, in many cases, be removed by modeling the photospheric velocity in addition to the optical light curve (although see Goldberg et al. 2019). Since the photospheric velocity itself is not observable, the FeII 5169 Å velocity is used as a proxy for the photospheric velocity. The photospheric velocity is generally calculated at an optical depth of $\tau = 2/3$, whereas the velocity of the FeII line is calculated in the Sobolev approximation, using a Sobolev optical depth $\tau_{\text{Sob}} = 1$. The Sobolev approximation and the resulting value of $\tau_{\text{Sob}}$ used in MESA are valid insofar as the ejecta are expanding homologously. Homologous expansion, however, is not reached until roughly 20–30 days post-explosion (Paxton et al. 2018). Therefore, the FeII velocities are not calculated de facto in the MESA code prior to 25 days. While it is possible to calculate them at earlier times, the numbers are unphysical and invalid if expansion is not homologous. In order to compare to the observed FeII 5169 Å at these early times, we use the photospheric velocity calculated at an optical depth $\tau = 2/3$. In our plots, we therefore show both calculated velocities: the FeII 5169 Å velocity from day 25 onward and the photospheric velocity from the time of explosion. Although the FeII velocities tend to be higher than the photospheric velocities during the plateau phase, Paxton et al. (2018) noted that there should be little difference between the two at early times. In summary, for each SN, we model the quasi-bolometric light curve, the light curves in the $UBVRI$ Johnson filters (or any of these that are provided), the FeII 5169 Å velocity, and the photospheric velocity.

We use the MESA test suite inlists example_make_pre_ccsn and example_ccsn_IIP to model the evolution of the star until the core-collapse SN phase. The main parameters that we vary are the ZAMS mass, mass-loss efficiency, and rotation velocity. Unless otherwise specified, all models referenced in this paper assume solar metallicity. For all models, overshooting and mixing-length parameters are the same as given in the MESA defaults: $f_{\text{ov}} = 0.01$, $f_{0.0v} = 0.004$, and $\alpha_{\text{MLT}} = 3.0$.

As an example of the stellar evolution modeling, in Figure 1, we show the H-R diagram for the evolution of the progenitor star of SN 2014cx. From our light-curve modeling, the best fit was produced for a progenitor ZAMS star of mass 12 $M_{\odot}$. The evolutionary track found from the model is as expected for the evolution of a 12 $M_{\odot}$ star (see, for instance, Ekström et al. 2012) that spends most of its life in the main sequence and ends its life as a RSG, giving rise to a Type IIP SN. The parameters of this star can be found in Table 1.

In Figure 2, we show the final density distributions (just before explosion) for the eight SN progenitor models computed in this paper. MESA allows a specified amount of CSM around the SN to be included, and we have found that doing so generally produces a better fit at early epochs, as was noted by Morozova et al. (2018, hereafter M18). This material, added by MESA just before the handoff to STELLA and presumably ejected in literally the last couple of years of the star’s life, has been found necessary to fit the initial light curves.
Table 2
Properties and Parameters of the SN Explosion Models

| SN        | $M_{\exp}$ ($M_\odot$) | $M_{\text{ej}}$ ($M_\odot$) | $R_{\exp}$ (R$_\odot$) | $t_{\text{CSM}}$ (yr) | $M_{\text{CSM}}$ ($M_\odot$ yr$^{-1}$) | $v_{\text{CSM}}$ (km s$^{-1}$) | $E_{\exp}$ (10$^{51}$ erg) | $M^{\text{Ni}}$ ($M_\odot$) | log($L_{\text{bol}}/L_\odot$) |
|-----------|--------------------------|-------------------------------|-------------------------|------------------------|------------------------------------------|-------------------------------|---------------------------|-----------------------------|-------------------------------|
| 1999em    | 11.83                    | 10.28                         | 682                     | 1.4                    | 0.15                                     | 10                           | 0.55                      | 0.075                       | 8.51                          |
| 2004et    | 13.69                    | 11.87                         | 792                     | 1.4                    | 0.30                                     | 10                           | 0.90                      | 0.100                       | 8.67                          |
| 2009bw    | 16.27                    | 14.26                         | 911                     | 1.4                    | 0.30                                     | 10                           | 0.64                      | 0.060                       | 8.52                          |
| 2013ab    | 9.57                     | 8.07                          | 536                     | 1.4                    | 0.15                                     | 10                           | 0.65                      | 0.065                       | 8.54                          |
| 2014cx    | 10.14                    | 8.66                          | 636                     | 1.4                    | 0.15                                     | 10                           | 0.70                      | 0.100                       | 8.62                          |
| ASASSN-14dq | 11.41                | 9.93                          | 629                     | 1.4                    | 0.30                                     | 10                           | 0.95                      | 0.075                       | 8.67                          |
| 2015ba    | 22.58                    | 20.17                         | 784                     | 1.4                    | 0.50                                     | 10                           | 0.85                      | 0.050                       | 8.59                          |
| 2016X     | 9.57                     | 8.07                          | 536                     | 1.4                    | 0.30                                     | 10                           | 0.60                      | 0.036                       | 8.52                          |

Note. The “SN” column lists the SN being modeled. Here $M_{\exp}$ is the progenitor mass at the time of explosion, $M_{\text{ej}}$ is the ejecta mass, $R_{\exp}$ is the progenitor radius at the time of explosion, $t_{\text{CSM}}$ is the number of years for the CSM wind artificially placed outside the model, $M_{\text{CSM}}$ is the mass-loss rate from this wind, $v_{\text{CSM}}$ is the wind velocity, $E_{\exp}$ is the total energy injected into the model during the SN explosion, and $M^{\text{Ni}}$ is the total $^{56}$Ni mass. The last column gives the bolometric luminosity of the optical light curve at 50 days post-explosion.

Once the stellar evolution model is completed, the SN is allowed to explode. Parameters for the explosion itself, such as total energy injection and $^{56}$Ni mass, are adjusted until a good match between the simulated and observed light curves is obtained. The light curves and Fe II velocities computed by STELLA are compared to the observations, and the model is refined until a suitable match is found. Although the parameters for SNe that have been modeled by other authors are given in the literature, there is considerable variation between these, and we do not regard them as a viable starting point. The effect of varying some parameters can be found in Paxton et al. (2018), although the cumulative effect of varying several parameters at a time can be more complex.

The number of variables involved in generating the light curves is extremely large. Tables 1 and 2 list the major parameters that were varied, but there may be cases where other stellar or explosion parameters may be needed. While one method of fitting observed and simulated light curves is to generate a large grid of light curves encompassing the entire range of values, this is not computationally feasible given the enormous range. Instead, we have chosen to use a combination of science, brute force, and our own experience in fitting the light curves, with the help of the parameter variations shown in Paxton et al. (2018) and a preliminary study. Inspecting the light curves and Fe II velocity, we decide on a range of initial values to use and then continually refine the parameters until what we deem is a reasonable fit is obtained. Often, as will be seen, the decision is not so clear, because a single parameter may make the bolometric or $UBVRI$ light curves better but the velocity worse, or vice versa, leaving us to determine which one should be given more weight or find a compromise. Given our eyeballing technique, we have not attempted to make any quantitative measurements of the goodness of fit.

M18 modeled the light curves of Type IIP SNe using the KEPLER stellar evolution code combined with the SNES radiation hydrodynamics code. They used a two-step fitting method employing a restricted grid of parameters, which they compared to the light curves. They did not compute and compare to photospheric velocities. For those SNe that are common between the two papers, we have provided a comparison between our results and theirs.

3. Light-curve Fits for SNe

As mentioned above, our standard technique involves fitting the quasi-bolometric light curve (a bolometric light curve derived from the individual $U$, $B$, $V$, $R$, and $I$ color curves); the $U$, $B$, $V$, $R$, and $I$ color curves themselves; and the Fe II 5169 Å velocity. In this section, we present the results of modeling the light curves of a set of SNe. After presenting the best-fit models for each SN, we compare our findings to prior results.

In total, we have considered eight SNe. Two of these, SN 1999em and SN 2004et, were chosen because they have been well studied in the past and allow us to compare our simulated parameters with those reported in the literature. We use these to verify that the MESA and STELLA computations provide reasonable results that fall within the range of acceptable values. It also allows us to check the agreement between the derived parameters and those obtained via other means, such as optical identification of progenitors, theoretical and multi-wavelength modeling, or hydrodynamical simulations.

Having assessed the validity of the MESA results, we proceed to tackle six more SNe that have not been widely studied in the literature. Some of these SNe have been reported as having progenitor masses in excess of 18 $M_\odot$, such as SNe 2014cx, ASASSN-14dq, 2015ba, and 2016X. For each SN, we present fits to the $UBVRI$ quasi-bolometric light curve; individual $U$, $B$, $V$, $R$, and $I$ color curves; and Fe II 5169 Å velocities. Our set of SNe is constrained by the requirement that all of this observational data be available to us. For many SNe, this was not the case, as no tables were provided. Often, the photospheric velocities were missing, as well as one or more of the necessary color curves. We made a minor exception in the case of SN 2015ba, an SN with a very interesting light curve that we decided to include despite its lack of data in the $U$, $R$, and $I$ bands. We have also tried to include a variety of SNe and discarded those with similar light curves and photospheric velocities to one already in our set. All quasi-bolometric light curve and Fe II 5169 observational data referenced throughout this paper have been digitized from available figures. Our STELLA runs used 120 frequency bins rather than the default 40 to better model the individual color curves.

Tables 1 and 2 summarize the parameters and properties for the evolutionary models and SN explosion from our light-curve fitting. Table 1 lists the model parameters, especially the ZAMS mass, rotation velocity (as a function of critical
velocity), metallicity, and wind efficiency. Table 2 gives the explosion parameters, such as the mass and radius of the star prior to explosion, the core mass, the wind properties that gave rise to the CSM, the explosion energy, the $^{56}\text{Ni}$ mass, and the plateau luminosity. We note that in what follows, we refer to the explosion energy of $10^{51}$ erg as 1 foe, as is often done in the literature. We use UT dates throughout this paper.

### 3.1. SN 1999em

A typical Type IIP SN, SN 1999em was discovered on 1999 October 20 at 22.4 UT in NGC 1637. We use 1999 October 24 (JD 2,451,476.0) as the explosion date, following Elmhamdi et al. (2003). Its plateau luminosity (Figure 3) is comparable to the average Type IIP (Figure 11), and the plateau duration is typical of the SNe presented here. We adopt a distance of 11.7 Mpc and reddening $E_{B-V} = 0.10$ mag, as found by Leonard et al. (2003) using the standard-candle method. We assume the ratio of total-to-select extinction to be $R_V = 3.1$ (Cardelli et al. 1989), giving a total line-of-sight extinction of $A_V = 0.31$. We compare our model to $UBVRI$ observational data from Leonard (2002) and Elmhamdi et al. (2003), with the quasi-bolometric light curve and Fe II 5169 velocity data digitized from figures in Huang et al. (2016, hereafter H16).

The best-fit MESA model for this SN, shown in Figure 3, provides very good agreement with the observed plateau and tail luminosities, as well as the plateau duration. We find a $^{56}\text{Ni}$ mass of 14 $M_\odot$ for the progenitor. Our results for the progenitor mass are comparable with those obtained via optical progenitor detection (Smartt 2009) and derived from X-ray and radio light curves (Pooley et al. 2002). The results are also consistent with the mass (12–14 $M_\odot$) and explosion energy ($0.5–1 \times 10^{51}$ erg) calculated by Elmhamdi et al. (2003) using the plateau brightness and duration and the expansion velocity. Elmhamdi et al. (2003), however, used a distance of 7.8 Mpc calculated by the expanding photosphere method. Their values for $^{56}\text{Ni}$ mass (0.02 $M_\odot$) and pre-SN radius (120–150 $R_\odot$) differ significantly from our results.

A ZAMS mass ranging from 20 to 21.5 $M_\odot$ and an explosion energy of 0.47 ± 0.05 foe, depending on the amount of $^{56}\text{Ni}$ mixed in, was found by M18. In this case, our explosion energy is in agreement with M18, but their ZAMS mass is 50% higher. The reason for this discrepancy between their modeling and ours is unclear, although it is possible that our modeling of the photospheric velocity contributes to our lower mass. It is clear from the results of Morozova et al. (2016) that there are substantial differences between the MESA + SNEC models as compared to the KEPLER + SNEC models, and we expect that these differences are further exaggerated when using MESA + STELLA. We remark on this further in Section 4.

### 3.2. SN 2004et

Discovered by S. Moretti at about 12.8 mag in NGC 6946 on 2004 September 27, SN 2004et is a bright SN and one of the better-studied SNe included in this paper. We use 2004 September 22.0 (JD 2,453,270.5) as the time of explosion for SN 2004et throughout this paper, following Li et al. (2005). They also found a distance of 5.5 Mpc and extinction $A_V = 1.27$ mag, which we adopt here. For this SN, we use observational data taken from Sahu et al. (2006). Progenitor mass estimates in the literature for this SN have encompassed a wide range. Various estimates that have been mentioned include 15–17 $M_\odot$ by Li et al. (2005), obtained by comparing the intrinsic color and absolute magnitude to stellar evolutionary tracks; 10–20 $M_\odot$, but closer to 20 $M_\odot$, by Misra et al. (2007) using the relations between various explosion parameters derived by Litvinova & Nadezhin (1985) and Popov (1993); ~20 $M_\odot$ by Chevalier et al. (2006), obtained by modeling the radio and X-ray light curves; 27 ± 2 $M_\odot$ by Utrobin & Chugai (2009) using hydrodynamic modeling; 9.2 $M_\odot$ by Smartt (2009) using direct optical progenitor detection; <15 $M_\odot$ by Jerkstrand et al. (2012), obtained by modeling the late-time spectra; and 16.5 $M_\odot$ by M18. Our best-fit model (Figure 4) has a ZAMS mass of 16 $M_\odot$, falling in the middle of the deduced range of values. It is in agreement with values obtained by Li et al. (2005), Misra et al. (2007), Jerkstrand et al. (2012), and M18 and close to the value obtained from direct progenitor detection. It is, however, lower than that found by Utrobin & Chugai (2009), who employed hydrodynamical modeling. A possible reason is that Utrobin & Chugai (2009) used what they term a nonevolutionary stellar model. Our explosion energy and $^{56}\text{Ni}$ mass estimates exceed those found by other methods. However, the good agreement between the simulated and observed light curves using these parameters at all but the earliest epochs suggests that our higher estimates are justified.
3.3. SN 2009bw

The unusual light curve of SN 2009bw has a bright initial peak followed by a long, flat plateau that falls off sharply at around 138 days post-explosion. It was discovered in UGC 2890 on 2009 March 27.87, leading to an assumed explosion date of ~2009 March 25 (JD 2,454,917.0; Inserra et al. 2012). Inserra et al. (2012) used hydrodynamical modeling to estimate an ejecta mass of 8.3–12 $M_\odot$, an explosion energy of 0.3 foe, and a $^{56}$Ni mass of 0.022 $M_\odot$. We compare our model to observational data from this paper. Our best-fit model (Figure 5), which adopts the distance of 20.2 Mpc and total reddening $E_{B-V} = 0.31$ mag used by Inserra et al. (2012), gives an ejecta mass of 14.26 $M_\odot$ (from a ZAMS mass of 18 $M_\odot$), an explosion energy of 0.64 foe, and a $^{56}$Ni mass of 0.060 $M_\odot$. We note that the best fit obtained by Inserra et al. (2012) was equally poor, if not worse. They suggested that weak circumstellar interaction may be playing a role in defining the light curve.

3.4. SN 2013ab

On 2013 February 17.5, Blanchard et al. (2013) discovered SN 2013ab in the galaxy NGC 5669. An explosion date of 2013 February 16.5 (JD 2,456,340.0) is adopted from Bose et al. (2015), who assumed a distance to the galaxy of 24 Mpc with a total extinction $A_v = 0.14$ mag. All observational data are taken from Bose et al. (2015). The SN exhibits a noticeably similar light curve to that of SN 1999em, with a slightly shorter plateau phase. Its Fe II 5169 Å velocity is also somewhat higher than that of SN 1999em for the first 80 days. Bose et al. (2015) calculated a total $^{56}$Ni mass of 0.064 $M_\odot$ by comparison to SN 1987A and from the tail luminosity (Hamuy 2003). They then used a general-relativistic, radiation-hydrodynamical model to estimate a progenitor mass at explosion of 9 $M_\odot$ and a radius of 600 $R_\odot$, with an explosion energy of 0.35 foe. Though they did allow for a somewhat lower energy with a different degree of $^{56}$Ni mixing, M18 found a progenitor ZAMS mass of 11.5 $M_\odot$ and an explosion energy of 0.84 foe. Our values are in good agreement with these, though the explosion energy in both our (0.65 foe) and M18’s calculations exceeds that of Bose et al. (2015). Our energy value arises primarily from fitting the Fe II velocity. Bose et al. (2015) used the Sc II lines to obtain the photospheric velocity, which is reasonable, but their best-fit
model (Figure 18 in their paper) clearly underestimates the velocity. They did consider a higher energy (0.6 foe, which would agree more with ours) to better match the velocities but found that it makes the light-curve fit much worse by lengthening the plateau phase. In our simulated model, the progenitor star is rotating at 35% of the critical velocity, an assumption that was not made in other analyses. The resulting model fits the observations remarkably well (Figure 6).

3.5. SN 2014cx

On UT 2014 September 2, SN 2014cx (ASASSN-14gm) was discovered in NGC 337 by Holoien et al. (2014) and Nakano et al. (2014). It was likely discovered within 1 day after the explosion and has an estimated explosion time of JD 2,456,902.4. Classification as a Type IIP followed by Elias-Rosa et al. (2014) and Andrews et al. (2015). We adopt for the host galaxy a distance of 18 \pm 3.6 Mpc and a total extinction of $A_V = 0.31$ mag, as used in H16. They deduced a $^{56}$Ni mass of 0.056 \pm 0.008 $M_{\odot}$ from comparison to SN 1987A or using the analytical formula derived by Hamuy (2003). Using hydrodynamical modeling, they found a mass at explosion of $\sim 10 M_{\odot}$ and a radius of 680 $R_{\odot}$, with an explosion energy of 0.4 foe. On the other hand, also using hydrodynamic modeling, M18 found a ZAMS mass of $> 22 M_{\odot}$ and an energy of 0.66 \pm 0.04 foe. Our simulated model, compared to the observational data from H16, reproduces the lower-mass estimate of H16. However, we find that a higher energy, as given by M18, is necessary to match the Fe velocities. We note that the model fit of H16 (Figure 12 in their paper) underestimates the photospheric velocity, especially in the first 2 months. Their model fit to the bolometric light curve is also not convincing. Our model (Figure 7) requires an especially high $^{56}$Ni mass to fit the nebular phase of the light curves. It fits the data well, with the exception of a slow rise time. This light curve is notable for having a short plateau, which in our stellar evolution model could only be adequately fit with a progenitor rotating at about a third of the critical velocity.

3.6. ASASSN-14dq

On 2014 UT July 08.48, ASASSN-14dq was discovered in the low-luminosity dwarf galaxy UGC 11860 (Stanek et al. 2014). Observational data are taken from Singh et al. (2018). Singh et al. (2018) estimated a mean distance to the host galaxy of 44.8 Mpc using the standard-candle method, with a total reddening $E_{B-V} = 0.06$ mag. Given the lack of existing measurements of the metallicity of this galaxy, Singh et al. (2018) estimated the metallicity using various luminosity–metallicity relations. They found a subsolar oxygen abundance for the host galaxy. Using model spectra generated for four 15 $M_{\odot}$ SN progenitors (Dessart et al. 2013) with metallicities of 0.1, 0.4, 1, and 2 $Z_{\odot}$, Singh et al. (2018) showed that the spectra matched closely with those at a metallicity $Z = 0.4 Z_{\odot}$. 

![Figure 6. Same as Figure 3 but for SN 2013ab.](image)

![Figure 7. Same as Figure 3 but for SN 2014cx.](image)
Using an analytic light-curve model, they estimated the ejecta mass from this SN to be ≈10 M☉, with an explosion energy of 1.8 foe and a total 56Ni mass of 0.029 M☉. Also, M18 found a progenitor ZAMS mass of 18.5–19.5 M☉ and an energy of 0.86 foe. We were unable to reproduce the light curves using a progenitor ZAMS mass of 18.5 M☉. They found a distance to the immediate progenitor at 860 ± 210 Mpc using the Tully-Fisher method and a total reddening of E_B-V = 0.04 mag. Based on the photospheric temperature, they estimated the radius of the immediate progenitor at 1.7 R☉, corresponding to a mass of 18.5–19.7 M☉. They found a 56Ni mass of 0.034 M☉ by comparing to SN 1987A. Our best fit to the light curves (Figure 10) gives significantly different parameters, with a ZAMS mass of only 11 M☉ and a radius of 536 R☉. Our value for 56Ni mass agrees well with the estimate of Huang et al. (2018). We find that the quasi-bolometric fit for this SN is poorer than that of many others examined in this paper. The plateau luminosity would appear to suggest a lower explosion energy, but the relatively large Fe velocities suggest the opposite. The comparison shown in Figure 10 represents a compromise between these two fitting parameters. Despite the difficulty in matching the quasi-

3.7. SN 2015ba

On 2015 November 28.8071 UT, SN 2015ba was discovered in the galaxy IC 1029. Dastidar et al. (2018) used a cross-correlation technique to determine the epoch of explosion, finally settling on 2015 November 23 (JD 2,457,349.7 ± 1.0) as the explosion date. Using a weighted mean of distances, they adopted a distance of 34.8 ± 0.7 Mpc and used a total reddening value of E_B-V = 0.46 mag. We use their values in this paper. The observational data referenced here also come from Dastidar et al. (2018) but are less complete than that of the other SNe studied in this paper. The U-band observations are missing, and RI data are incomplete, so the quasi-bolometric light curve is calculated using the BVri bands rather than the standard UBVRI. This SN is notable for an unusually long, flat plateau, which ends in a sharp drop of ~3 mag. In fact, there does not appear to be another well-studied Type IIP SN with a plateau as luminous and long as that of SN 2015ba (Anderson et al. 2014; Dastidar et al. 2018).

Dastidar et al. (2018) found a 56Ni mass for this SN of 0.032 M☉. Using analytical and general-relativistic, radiation-hydrodynamical modeling, they estimated the ejecta mass at 22–24 M☉ and the explosion energy at 1.8–2.5 foe. In our modeling, we find that a similarly large progenitor mass is necessary in order to produce a long light curve with a large drop in luminosity in the nebular phase. However, even using larger progenitor masses, we were unable to fit the observed light curves for SN 2015ba with the same precision that we obtained for the other SNe in this paper. Our best model, with a mass of 24 M☉, an explosion energy of 0.85 foe, and a 56Ni mass of 0.050 M☉, still does a poor job of modeling the sharp drop-off from the plateau to the nebular phase (see Figure 9). A small part of this inconsistency may be due to our comparison of the UBVRI quasi-bolometric light curve generated by STELLA to the BVri quasi-bolometric curve derived from observations, but we do not expect this to be the major issue. The U-band light curves tend to fall off more gradually than the other bands due to cooling of the material and degradation of photons. Given this shortcoming, our best-fit parameters for SN 2015ba have greater uncertainty than those for the other SNe modeled in this paper. What is clear, though, is that the progenitor mass is very high compared to those of the other SNe and likely in the same ballpark as that estimated by Dastidar et al. (2018).

3.8. SN 2016X

Of all the SNe investigated in this paper, SN 2016X is the least luminous and has the shortest plateau. It was discovered by the All Sky Automated Survey for SuperNovae (ASAS-SN) on 2016 January 20.59 UT in the nearby SBd galaxy UGC 08041 (z = 0.004 408 from NED). An explosion date of 2016 January 18.9 (JD 2,457,406.4) was adopted by Huang et al. (2018). All observational data referenced here are taken from Huang et al. (2018). They found a distance to the host galaxy of 15.2 Mpc using the Tully-Fisher method and a total reddening of E_B-V = 0.04 mag. Based on the photospheric temperature, they estimated the radius of the immediate progenitor at 860–990 R☉, corresponding to a mass of 18.5–19.7 M☉. They found a 56Ni mass of 0.034 M☉ by comparing to SN 1987A. Our best fit to the light curves (Figure 10) gives significantly different parameters, with a ZAMS mass of only 11 M☉ and a radius of 536 R☉. Our value for 56Ni mass agrees well with the estimate of Huang et al. (2018). We find that the quasi-bolometric fit for this SN is poorer than that of many others examined in this paper. The plateau luminosity would appear to suggest a lower explosion energy, but the relatively large Fe velocities suggest the opposite. The comparison shown in Figure 10 represents a compromise between these two fitting parameters. Despite the difficulty in matching the quasi-
bolometric light curve, the individual UBVRI light curves compare fairly well and clearly require a progenitor mass well below the estimate of Huang et al. (2018).

4. Summary and Discussion

4.1. Quality of the Fits

In this paper, we have simulated the quasi-bolometric light curves, UBVRI color light curves, and photospheric velocities for eight SNe and compared these to the observational data. We have used the best-fit models to determine the properties of the explosion, such as the explosion energy and $^{56}$Ni mass, as well as the properties of the progenitor star, in particular, the ZAMS progenitor mass. The quasi-bolometric light curves and Fe II 5169 Å velocities for all of the SNe covered in this paper are shown in Figure 11.

Overall, we find that a good fit to the quasi-bolometric curve typically results in a good fit to the color curves, though this is less true in the cases of SNe 2009bw and 2016X. The $U$ and $B$ fits tend to be poorer than the $V$, $R$, and $I$ fits, though these are still fairly good in most cases.

There is undoubtedly some leeway in the parameters for each SN, although the specific error in each case is difficult to quantify. Given the good fit in most cases, we suspect that this uncertainty is quite low, and we are confident that in most cases, the progenitor masses are determined to within about a solar mass. Figure 12 gives the best-fit model for SN 2004et alongside otherwise identical models with $\pm 2 M_\odot$ at ZAMS. These models have clearly diverged from the best fit: the 14 $M_\odot$ model has good Fe II 5169 velocity agreement but produces a less luminous and shorter plateau. Adjusting other parameters does not improve the fit. The larger 18 $M_\odot$ model does appear to fit the light curve reasonably but gives Fe II 5169 velocities that are too high. Adjusting these to be more in line with the data would require lowering the explosion energy, which would, in turn, increase the plateau length, thereby destroying the light-curve fit.

There do not appear to be any significant degeneracies, i.e., models with similar features but drastically different parameters, among our model fits. Requiring matches to all of the bolometric light curves, UBVRI color curves, and Fe II velocities helps to eliminate some degeneracy, as exemplified by the models mentioned above. Goldberg et al. (2019) found that some degeneracy exists between models with various initial masses in MESA/STELLA when matching both the bolometric light curves and the Fe II velocities. However, they did not additionally compare the UBVRI color light curves, which would certainly help. Furthermore, they argued that early-time Fe velocities, which are shown to vary greatly based on explosion energy and the compactness of the progenitor star, can be used to eliminate the degeneracy in cases where there is
no substantial CSM present. Given the difficulty in obtaining the early Fe II velocities mentioned in Section 2, we have used the photospheric velocity at early times instead. All of our models succeed in matching the early SN velocities, and we note that these early velocities help us to eliminate degenerate models even with some CSM present.

In their comparison of Type IIP SN light curves using the KEPLER and SNEC codes, M18 often found much higher progenitor masses than we find in this paper. However, they did not compute the Fe II 5169 velocities, which, as shown in the above example, are essential to breaking the degeneracy in progenitor mass and explosion energy.

The SN progenitor models produced using MESA and STELLA were found to be quite capable of reproducing the light curves and photospheric velocities of Type IIP SNe. We used the sample routines as described in Paxton et al. (2018) to carry out the stellar evolution modeling and SN explosion, modifying a minimal number of parameters required to get the evolution correct. We did not change the technique employed to explode the SN. In our work, we found that there are certain features of the light curves that STELLA seems to have difficulty with. The U and B color curves tend to fit much worse than the V, R, and I curves, especially at later times. (We address this in detail at the end of this section.) Furthermore, the rise time in our models is generally too long. Some of this may be due to the uncertainty in the explosion times. It was observed by M18 that STELLA produces rise times 3–5 days longer than those obtained using SNEC, which we appear to see in our models. Additionally, early peaks in the light curves tend to be a problem for STELLA, especially when using a large number of frequency bins. Although the addition of a large amount of CSM does help in this regard, it often proves inadequate, such as for SNe 2004et, 2009bw, and 2015ba.

Furthermore, we found the modeling of several subluminous SNe, including SNe 2009N and 2005cs, to be problematic using the techniques outlined herein. Reproducing the dim plateaus of these SNe proved difficult without the use of exceedingly low explosion energies, which resulted in significantly lower Fe II 5169 velocities. Adjustments to mixing length and overshooting appear to be promising avenues toward reproducing these subluminous light curves and will be explored in future work. Notwithstanding all this, STELLA generally does an excellent job reproducing the most important features of standard SN light curves and is an excellent addition to the suite of tools available to an SN astronomer.

The majority of the fits presented in this paper indicate SN progenitor masses that overlap with some of the previous estimates, with the exception of SN 2016X. We find that the MESA and STELLA combination used in this paper tends to give lower progenitor masses than previous hydrodynamical modeling techniques (see Section 3.2) and typically agrees with the general-relativistic, radiation-hydrodynamical code that has been used to model SNe 2009bw, 2013ab, 2014cx, and 2015ba by Inserra et al. (2012), Bose et al. (2015), H16, and Dastidar et al. (2018), respectively. The modeling done by M18 using SNEC agrees with our own in the cases of SNe 2004et and 2013ab but produces significantly higher progenitor masses for SNe 1999em, 2014cx, and ASASSN-14dq.
In order to study the differences between our model fits and those calculated by others, we have input the best-fit parameters obtained by other codes in our MESA/STELLA combination. Figure 13 shows our best-fit model for SN 2014cx alongside models produced in MESA using the explosion parameters derived by H16 and M18, as given in Section 3.5. While the original KEPLER/SNEC model presented in M18 lines up quite well with the observational data, our M18-inspired MESA model shows a much larger discrepancy with the observational data. As discussed in detail below, 56Ni mixing may account for some of this divergence. In the case of H16, the original general-relativistic, radiation-hydrodynamical code model presented in their paper did not fit the data as accurately as ours or M18’s. However, the MESA recreation of this model does not even properly reproduce the shape of the light curve. We were forced to reuse our rotating 12 solar mass model in this case, as MESA failed to explode a similarly sized nonrotating model, but the presence of rotation should not cause nearly the degree of variation we observe here. Due to the complexity of these codes and the large number of parameters involved, the reasons for such significant disagreement between the three remain unclear. However, it is clear that the differences in the best-fit parameters arise to a substantial degree due to the differences in the codes themselves, both in the stellar evolution modeling and the light-curve modeling. An unfortunate conclusion from this may be that the results from all codes are suspect. However, in our opinion, the results from MESA + STELLA appear to be more in line with observations. To be certain, MESA also has its shortcomings, but the large user base makes it likely that problems will be caught early. To the developers’ credit, they are continually and actively working to add more physics modules while improving the code and fixing errors, as the series of MESA papers shows.

In the past, hydrodynamical models of Type IIP SNe generally required much higher progenitor ZAMS masses. This has been attributed to the use of nonevolutionary models, or spherically symmetric models that do not take hydrodynamic instabilities and mixing into account. Both of these problems are rectified in this version of MESA and STELLA to some degree. Although the SN explosion models are one-dimensional, they do take the multidimensional effects of the Rayleigh–Taylor instability (RTI) and mixing into account using the prescription by Duffell (2016). The Duffell RTI scheme is applied by MESA to 56Ni mixing during the SN explosion. The degree of 56Ni mixing has been shown to have a significant effect on SN light curves, and this process has typically been handled in the past by adding 56Ni uniformly out to a chosen mass coordinate (Bersten et al. 2011; M18). MESA takes a different approach, first adding 56Ni uniformly out to a mass coordinate consistent with 3D simulations (see Figure 27 in Paxton et al. 2018) just before the shock reaches the H shell. The 56Ni distribution is then allowed to evolve through the Duffell RTI until just before shock breakout, at which point the resulting distribution is rescaled in place to match the chosen total 56Ni mass. This dynamic process produces smoothly mixed final distributions like those shown in Figure 14, which vary as expected with ZAMS mass but are generally consistent. In our runs, we have not altered the default parameters used by MESA for the Duffel RTI, since it was shown in Paxton et al. (2018) that the effect is relatively small.

As noted above, the U and B color curves in our models often fall off faster than the observations at later epochs. A similar behavior was noted by Blinnikov et al. (2006) when using STELLA. They attributed it to a large degree of 56Ni mixing, which leads to a more rapid evolution. This is exactly the behavior that we see, for instance, in SN 2016X (Figure 10), where the early-time U-band flux matches the peak well but decreases faster than the observed flux. In the case of ASASSN-14dq (Figure 8), the U-band flux is somewhat higher than the observed flux at early times but lower than the observed one at late times. It is possible that reducing the mixing may be beneficial to the late-time light curves but may affect the early-time flux adversely, as well as the other colors. It may be necessary to somehow reduce the mixing proportionately in the outer layers, which is beyond the scope of this work.

### 4.2. Explosion and Progenitor Properties

In Section 1 the RSG problem was brought up, asserting that RSGs that exploded to form Type IIP SNe had ZAMS progenitor masses $\lesssim 17–19 M_\odot$. Though the X-ray limit is not well constrained, what is important is that a mass limit exists that is lower than the maximum mass of an RSG, as deduced from stellar evolution theory. A partial explanation may arise from theoretical modeling, with Sukhbold et al. (2016)
claiming that only about 10% of SNe arise from stars $>20 M_\odot$, and some of these are Type Ib or Ic. They find that there are only small “islands” of progenitor masses above $20 M_\odot$, where stars undergo core collapse to form an SN.

For the most part, our results are consistent with the assertions of Sukhbold et al. (2016). Seven of our eight SNe indicate progenitor masses lower than $18 M_\odot$. The fit to SN 2015ba suggests a ZAMS mass in excess of this value, although the poor quality of the fit does not allow for any firm conclusions, especially given that the light curve does not resemble the other Type IIP SN light curves studied herein (see Figure 11). Given our small sample size and the fact that many of these SNe were thought to have much larger progenitor masses in the past, one out of eight, or 12.5%, having a progenitor mass above $20 M_\odot$ is in keeping with theoretical expectations.

The $^{56}\text{Ni}$ masses presented in this paper are obtained directly from the fits, without appealing to (semi-)analytic values or comparing to another SN, such as SN 1987A. They appear well constrained, as the $^{56}\text{Ni}$ mass almost exclusively determines the luminosity of the radioactive tail of the plateau for a given ZAMS mass. Many of the $^{56}\text{Ni}$ masses referenced in the literature are derived by comparison to the bolometric light curve of SN 1987A, as in Hamuy (2003). Our values are generally larger than those previously found, with the exception of SNe 2013ab and 2016X. However, they still show a direct correlation between $^{56}\text{Ni}$ mass and tail luminosity.

Müller et al. (2017) calculated a relation between $^{56}\text{Ni}$ mass and plateau luminosity,

$$\log \left( \frac{M_{^{56}\text{Ni}}}{M_\odot} \right) = 1.55^{+0.16}_{-0.14} \log \left( \frac{L_{\text{pl}}}{L_\odot} \right) - 14.51^{+1.21}_{-1.24},$$

where $L_{\text{pl}}$ is the bolometric luminosity at 50 days post-explosion. The values obtained from our fits are in reasonable agreement with this relation (see Figure 15), as well as with relations found by Pejcha & Prieto (2015).

The explosion energies for the various SNe derived from our model fits do not compare well with those found in previous work. No clear pattern emerges between explosion energies derived from STELLA and those from either SNEC or general-relativistic radiation-hydrodynamical models. As noted, though, many of the fits calculated with the latter seemed to underestimate the photospheric velocities and would therefore suggest a higher explosion energy. Figure 16 shows the comparison of our values with the relation between $^{56}\text{Ni}$ mass and explosion energy derived for a large sample of SNe by Müller et al. (2017), using the scaling relations of Litvinova & Nadezhin (1985; black) and Popov (1993; brown). The linear relations and their intrinsic widths are shown as solid and dashed lines, respectively.
A similar relation was also derived by Müller et al. (2017) using the scaling relations of Popov (1993):

$$\log \left( \frac{M_{\text{56Ni}}}{M_\odot} \right) = 1.30^{+0.28}_{-0.21} \log \left( \frac{E_{\text{exp}}}{10^{50}} \right) - 2.62^{+0.21}_{-0.16}. \quad (3)$$

Our values indicate a higher $^{56}$Ni mass for a given explosion energy compared to both calibrations, with a large spread in values. The systematic errors in our estimates are difficult to quantify, given that they may depend on factors in the stellar evolution, explosion mechanism, or mixing. A larger sample size of SNe might provide a stronger correlation, but given that all eight of our SNe fall above both Müller et al. (2017) relations, this seems unlikely. It was shown by M18 how the explosion energy can vary depending on the degree of $^{56}$Ni mixing. Pejcha & Prieto (2015) showed that there is an inherent degeneracy between $^{56}$Ni mass and explosion energy that makes the correlation weak. It is clear from Figure 3 in Müller et al. (2017) that although there may be a correlation between the $^{56}$Ni mass and explosion energy, the scatter in the values is large. Figure 10 in M18 shows an equally large spread of values.

5. Conclusions

We have used the STELLA code included in the newest release of MESA to determine the progenitor properties for a sample of eight Type IIP SNe. We find that the version of STELLA provided is adequate to model both the light curves and Fe II 5169 velocities for a wide range of SNe. It is able to provide reasonably well-constrained SN parameters, such as the progenitor ZAMS mass, total explosion energy, and synthesized $^{56}$Ni mass, among others. In the past, hydrodynamical models have generally returned progenitor ZAMS masses much higher than those derived by optical progenitor identification via X-ray or radio modeling or late-time spectral modeling. This was also true to some degree in the work of M18. In our work, we do not find this. Of the eight SNe investigated in this paper, we find that seven have progenitor ZAMS masses of $\leq 18 M_\odot$, with most in the 11–14 $M_\odot$ range. These results are in agreement with past reports indicating that the majority of observed Type IIPs have low-mass progenitors. We do find one exception in SN 2015ba, whose light curve is clearly atypical compared to other Type IIP SNe (Figure 11). This SN likely requires a ZAMS mass around 24 $M_\odot$, though our inability to accurately reproduce the light curve of this particular SN introduces large uncertainties into this result. We note that this is not completely unexpected—Sukhbold et al. (2016) claimed that while most Type II SNe should arise from below 20 $M_\odot$, ~10% of SNe arise from higher-mass stars.

The $^{56}$Ni masses in our study, although high, appear to fit within the calibration of Müller et al. (2017) for the $^{56}$Ni mass against the plateau luminosity at 50 days. This would perhaps question the accuracy of $^{56}$Ni masses derived from comparisons with the $^{56}$Ni value in SN 1987A. However, when plotted against the explosion energy following the relationships derived by Müller et al. (2017), we find that our $^{56}$Ni masses appear high for the derived energy. Overall, while accepting that our data set is small, our values do not reflect tight relationships between any of the parameters of $^{56}$Ni mass, explosion energy, progenitor mass, and plateau luminosity. We agree with the results of both Pejcha & Prieto (2015) and Gutiérrez et al. (2017), who found that SN explosions are not described by a single parameter but by a range of parameter values.

We thank the anonymous referee for a comprehensive reading of the paper and insightful comments and suggestions that helped to improve it substantially. This work is supported by NASA Astrophysics Data Analysis program grant No. NNX14AR63G awarded to PI V.V.D. at the University of Chicago. This work has made use of the MESA stellar evolution code, and we are deeply grateful to the authors. We especially thank Bill Paxton and Jared Goldberg for patiently answering all of our questions about the way MESA works and Sergei Blinnikov for doing the same with the STELLA code. We acknowledge useful discussions with Pablo Marchant and Mathieu Renzo.

Software: MESA (Paxton et al. 2011, 2013, 2015, 2018), STELLA (Blinnikov et al. 1998, 2006; Blinnikov & Sorokina 2004).

ORCID iDs

Wilson Ricks @ https://orcid.org/0000-0003-3385-1605
Vikram V. Dwarkadas @ https://orcid.org/0000-0002-4661-7001

References

Adams, S. M., Kochanek, C. S., Gerke, J. R., Stanek, K. Z., & Dai, X. 2017, MNRAS, 468, 4968
Anderson, J. P., González-Gaitán, S., Hamuy, M., et al. 2014, Apl, 786, 67
Andrews, J., Smith, N., Fong, W.-f., & Milne, P. 2015, ATeL, 7084
Bersten, M. C., Benvenuto, O., & Hamuy, M. 2011, Apl, 729, 61
Bessell, M. S. 2005, ARA&A, 43, 293
Blanchard, P., Zheng, W., Cenko, S. B., et al. 2013, CBET, 3422
Blinnikov, S., & Sorokina, E. 2004, ApsSS, 290, 13
Blinnikov, S. I., Eastman, R., Bartunov, O. S., Popolitov, V. A., & Woosley, S. E. 1998, Apl, 496, 454
Blinnikov, S. I., Röpke, F. K., Sorokina, E. I., et al. 2006, A&A, 453, 229
Bose, S., Valenti, S., Mista, K., et al. 2015, MNRAS, 450, 2373
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, Apl, 345, 245
Chevalier, R. A., Fransson, C., & Nynmark, T. K. 2006, Apl, 641, 1029
Das, S., & Ray, A. 2017, Apl, 851, 138
Dasdilar, R., Misra, K., Hosseinzadeh, G., et al. 2018, MNRAS, 479, 2421
Davies, B., & Beasor, E. R. 2018, MNRAS, 474, 2116
Dessart, L., Hillier, D. J., Waldman, R., & Livne, E. 2013, MNRAS, 433, 1745
Duffell, P. C. 2016, Apl, 821, 76
Dwarkadas, V. V. 2014, MNRAS, 440, 1917
Ekström, S., Gregory, C., Eggenberger, P., et al. 2012, A&A, 537, A146
Ekström, S., Gregory, C., Meynet, G., Groh, J., & Granada, A., 2013, in EAS Publ Ser. 60, Betelgeuse Workshop 2012, ed. P. Kervella, T. Le Bertre, & G. Perrin (Les Ulis: EDP Sciences), 31
Eldridge, J. J., Fraser, M., Smartt, S. J., Maund, J. R., & Crockett, R. M. 2013, MNRAS, 436, 774
Elias-Rosa, N. 2016, IAUFSM, 29, 209
Elias-Rosa, N., Tartaglia, L., Cappellaro, E., et al. 2014, ATeL, 6440
Elmhamdi, A., Danziger, I. J., Chugai, N., et al. 2003, MNRAS, 338, 939
Faran, T., Poznanski, D., Filippenko, A. V., et al. 2014, MNRAS, 442, 844
Gal-Yam, A., Leonard, D. C., Fox, D. B., et al. 2007, Apl, 656, 372
Gaskell, C. M., Cappellaro, E., Dinerstein, H. L., et al. 1986, AplL, 306, L77
Georgy, C., Ekström, S., Meynet, G., et al. 2012, A&A, 542, A29
Goldberg, J. A., Bildsten, L., & Paxton, B. 2019, Apl, 879, 3
Gutiérrez, C. P., Anderson, J. P., Hamuy, M., et al. 2017, Apl, 850, 90
Hamuy, M. 2003, Apl, 582, 905
Hendry, M. A., Smartt, S. J., Czekier, R. M., et al. 2006, MNRAS, 369, 1303
Hillebrandt, W., Kromer, M., Röpke, F. K., & Rüiter, A. J. 2013, Frhly, 8, 116
Holoiyen, T. W.-S., Prieto, J. L., Kochanek, C. S., et al. 2014, ATeL, 6436
Horiuchi, S., Nakamura, K., Takiwaki, T., Kotake, K., & Tanaka, M. 2014, MNRAS, 445, 1,999
Huang, F., Wang, X., Zampieri, L., et al. 2016, Apl, 832, 139
Huang, F., Wang, X.-F., Hosseinzadeh, G., et al. 2018, MNRAS, 475, 3959
Inserra, C., Turatto, M., Pastorello, A., et al. 2012, MNRAS, 422, 1122
