Modeling Type II-P/II-L Supernovae Interacting with Recent Episodic Mass Ejections from Their Presupernova Stars with MESA and SNEC

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Abstract

We show how dense, compact, discrete shells of circumstellar gas immediately outside of red supergiants affect the optical light curves of Type II-P/II-L supernovae (SNe), using the example of SN 2013ej. Earlier efforts in the literature had used an artificial circumstellar medium (CSM) stitched to the surface of an evolved star that had not gone through a phase of late-stage heavy mass loss, which, in essence, is the original source of the CSM. In contrast, we allow enhanced mass-loss rate from the modeled star during the 16O and 28Si burning stages and construct the CSM from the resulting mass-loss history in a self-consistent way. Once such evolved pre-SN stars are exploded, we find that the models with early interaction between the shock and the dense CSM reproduce light curves far better than those without that mass loss and, hence, having no nearby dense CSM. The required explosion energy for the progenitors with a dense CSM is reduced by almost a factor of two compared to those without the CSM. Our model, with a more realistic CSM profile and presupernova and explosion parameters, fits observed data much better throughout the rise, plateau, and radioactive tail phases as compared to previous studies. This points to an intermediate class of supernovae between Type II-P/II-L and Type II-n SNe with the characteristics of simultaneous UV and optical peak, slow decline after peak, and a longer plateau.

Key words: circumstellar matter – hydrodynamics – radiative transfer – stars: mass-loss – supernovae: general – supernovae: individual (SN 2013ej)

1. Introduction

Massive stars (with zero age main sequence (ZAMS) mass >8 M⊙) end their lives as core-collapse supernovae (CCSNe). Type II SNe, a class of CCSNe, are identified by the P-Cygni profile of hydrogen in their early spectra. Type II-P supernovae (SNe) comprise a large fraction (~48%) of nearby core-collapse SNe population within 60 Mpc (Smith et al. 2011). These have pronounced plateaus in their visible band light curves that remain within ∼1 mag of maximum brightness for an extended period, e.g., 60–100 rest frame days, and is followed by exponential tail at late times (Faran et al. 2014a). Based on photometric and spectroscopic analysis, Type II-L SNe are separately classified from II-P by their larger rise time, brighter peak, faster and linearly falling luminosity after peak and around ~50 days, higher Hα velocity, larger ratio of Hα emission to absorption, slowly evolving Hβ velocity, and bluer color curves with an average decline rate βH > 3.5 mag/100 days (Barbon et al. 1979; Patat et al. 1993, 1994; Arcavi et al. 2012; Faran et al. 2014b; Gutiérrez et al. 2014; Gall et al. 2015). At the same time, several studies with large samples show that Types II-P and II-L SNe form a continuous and statistically indistinguishable class of CCSNe (Young & Branch 1989; Anderson et al. 2014; Sanders et al. 2015). Despite their quantitative differences in light curve patterns and spectroscopic features, different groups of researchers (Grassberg et al. 1971; Swartz et al. 1991; Blinnikov & Bartunov 1993) have tried to find a range of progenitors that would lead to a continuous transition of the properties of type II-P to II-L explosions, in view of the possible variation of the plateau length and the associated parameters with the mass and radius of the hydrogen envelope (Litvinova & Nadezhin 1983; Nomoto et al. 1995). However, so far it has not been possible to simulate Type II-L explosions as an extreme case of Type II-P SNe (Morozova et al. 2015). On the other hand, Type II-n SNe (Schlegel 1990) show in their early spectra narrow hydrogen Balmer emission lines, or P-cygni profiles, on top of broad emission lines. A particularly interesting example, SN1994W, shows the presence of three components in their first three months consisting of narrow P-cygni lines with absorption minimum at 700 km s−1, a broad emission line with a blue edge at ∼4000 km s−1, and broad smooth wings extended to at least 5000 km s−1 in H-α and H-β. Chugai et al. (2004) attributed these components to a dense circumstellar envelope, a shocked, dense-but-cool gas confined right on top of the photosphere, and the effects of Thompson scattering in the circumstellar envelope. The plateau-like light curve of the supernova modeled by hydrodynamic simulations showed that the pre-explosion kinematics of the circumstellar envelope for a high mass (~0.4 M⊙) and kinetic energy (~2 × 1048 erg) of the envelope that must be ejected ~1.5 years prior to the explosion. A close cousin of SN1994W is SN2011ht, which also shows a plateau and subsequent exceptionally faint and steeply declining light curve in its nebular phase, prompting Mauerhan et al. (2013) to propose a new subclass of Type II-np-interacting SNe with a plateau light curve phase. Typically Type II-n SNe have large rise time (~20–50 days), very bright peaks of M_B = −18.4 ± 1.0 mag, and a large range of decline rate spanning from flat plateau events similar to II-P SNe to rapidly decaying events similar to II-b SNe (Kiewe et al. 2012). These works support the association of II-n SNe with luminous blue variable (LBV) stars.
Type II-P/II-L and II-n SNe have been traditionally differentiated due to their observed characteristics and inferred progenitor properties. Recently, there has been consideration of the effect of dense circumstellar material immediately outside of the progenitors on the early light curves of Type II-P/II-L SNe (Valenti et al. 2015; Morozova et al. 2017; Yaron et al. 2017) and a subclass of moderately interacting SNe has been identified. This subclass may comprise an intermediate class of SNe between Types II-P/II-L and II-n SNe (Smith et al. 2015) and their progenitors may fill the gap between the observed ZAMS mass range of their respective progenitors (Moriya et al. 2011).

Here we have evolved the stars in MESA: Modules for Experiments in Stellar Astrophysics5 (Paxton et al. 2011, 2013, 2015) from their pre-ZAMS stage until the Fe core collapse with a history of enhanced mass-loss rate in the last few years, and constructed the circumstellar medium (CSM) from the information of that episodic mass ejection during the late-stage evolution of the star. Our method is self-consistent in two ways. First, because the simulation of enhanced mass loss over a timescale of few years reveals the impact on surface properties (mainly luminosity and radius) naturally from the stellar evolution (Figure 2), the pre-SN progenitor carries the trace of the phenomenon with it. Second, the modeling of the CSM also accounts for these changes in the star, and thus the CSM profile becomes more realistic. This is in contrast with the earlier works on the effect of CSM on Type II-P SNe, where artificial CSM is designed assuming a constant ratio of mass-loss rate and wind speed, and the profile is stitched to the pre-SN star that is independently modeled by stellar evolution codes (e.g., KEPLER or MESA) without any huge mass-loss history (Moriya et al. 2017; Morozova et al. 2017). We explore the progenitor with CSM using SNEC: Supernova Explosion Code6 (Morozova et al. 2015) and compare its light curve to the light curve of the explosion resulting from a progenitor with no excess mass loss history and hence no dense CSM in the immediate vicinity of the exploding star. We make a comparative study of the models best fitting the optical and near-infrared (NIR) light curves of SN 2013ej and show how the models with dense CSM improve the fit. We also compare our best-fitted model with those reported in earlier work (Morozova et al. 2017) to show how our model is more physically realistic and how the model better describes the observed data over a longer timescale. A preliminary version of this work was presented at the IAU Symposium 331 (Das & Ray 2017).

2. Methods and Simulations

Early spectroscopic observations of SN 2013ej in its host galaxy NGC 628 (M74) confirmed it as a young Type II supernova (Valenti et al. 2013). Photometric and spectro-polarimetric observations classified it as a Type II-P supernova with unusually strong early-time polarization (Leonard et al. 2013). Later it was marked as a Type II-L supernova because of the relatively faster decline (1.74 mag/100 days) of light curve in intermediate phase (Bose et al. 2015). We simulate and study the evolution of the progenitor of SN 2013ej in three steps: the evolution from pre-main-sequence (MS) to post-MS until ~20 years before collapse, the last two decades until a few (~2–3) years before collapse, and the last 2–3 years. The final state is exploded to investigate the optical and NIR light curves.

2.1. Progenitor Evolution in the Late Stage and Circumstellar Medium

We have taken the metallicity (=0.295Z⊙) of the H II region near the site of the explosion (region no. 197 reported in Cedrés et al. 2012) and ZAMS mass range of 12–19 M⊙ in step of 1 M⊙ for all of our MESA models of nonrotating single stars.7 Although the upper mass limit of Type II-P SNe progenitors observed from the pre-explosion images is found to be ZAMS mass of 17 M⊙ (Smartt et al. 2009), higher masses of red supergiants (~ZAMS mass of 25 M⊙) have been observed in Milky Way and other galaxies. Also, models of single stars between 8 and 25 M⊙ leading to successful II-P/L SNe have been predicted. This has led to the so-called “red supergiant problem.”8 So far, the hydrodynamical models of Type II-P SNe (Utrobin & Chugai 2008, 2009) have not been able to achieve a reasonably close upper limit of mass of 17 M⊙. We use Ledoux criterion for convection, and take mixing parameters following Morozova et al. (2016). We keep the average long-term mass loss rate around ~10−6M⊙ yr−1 using Vink’s scheme for hot (T > 10⁴ K) wind with η = 1 and Dutch scheme for cool wind with η = 1 and 0.5 (de Jager et al. 1988; Nieuwenhuijzen & de Jager 1990; Vink et al. 2001). It was constrained by X-ray studies of Chakraborti et al. (2016), which probed the mass-loss rate of the progenitor of SN 2013ej in the range of 40–400 years before the explosion.

To constrain the ZAMS mass we convert the Hubble Space Telescope (HST) magnitudes (F435W, F555W and F814W) into Johnson’s photometric system (B, V, and I) using the algorithm proposed in Sirianni et al. (2005) and compare the archival HST Wide Field Camera (WFC) images of 2003 November and 2005 June with our simulated models in MESA.8 While the studies by Kochanek et al. (2017) from the same observations of Fraser et al. (2014) over 5 years (2003–2008) do not find any variability on an average, we find a somewhat noticeable reduction in V magnitude (ΔmV = 0.32, with σ ∼ 0.2 mag) and hence an increase in V − I color (Δ(V − I) = 0.31, with σ ∼ 0.28 mag) in a smaller timescale (from 2003 November to 2005 June), which suggests possible temporal changes in between. Our assumption is supported by the finding of Davies & Beasor (2017), who shows that RSGs may evolve in spectral types as they approach the final stage. We relate this to the absorption and reddening by dust formed in the CSM nearby. An optimized combination of enhanced mass-loss rate, duration, and instance of enhanced

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5 http://mesa.sourceforge.net/index.html
6 https://stellarcollapse.org/SNEC
7 Fraser et al. (2014) identified a nearby source in the archival images of its progenitor. The distance between the two (~2 pc) eliminated the possibility of it being a part of a binary system.
8 However, a recent study of the initial masses of the RSG progenitors to Type II-P SNe by Davies & Beasor (2017), investigating the systematic error due to large bolometric corrections (BDCs) using RSGs in star clusters, and accounting for finite sample sizes of direct observations of the SN progenitors raises the upper limit of progenitors to upwards of 25 M⊙ (95% confidence limit of <33 M⊙), thus eliminating any strong evidence of “missing” SN progenitors with ZAMS mass >17 M⊙.
9 Fraser et al. (2014) identified a nearby source dominating in bluer wavelengths, which explained the unusual B − V color of the candidate supernova. Therefore, the B band magnitude, partially contaminated by the unrelated source, is not used to constrain the mass limit.
mass loss provided the required CSM extinction (see Appendix B), and this gave an upper limit of ZAMS mass 14 M☉ (Figure 1). It is consistent with the upper limit inferred from the same archival image observation of Fraser et al. (2014) and the nebular phase observation of Yuan et al. (2016) as well. The existence of circumstellar dust, which has a smaller absorption coefficient in larger wavelengths ($Q_{abs}(\lambda = 0.1 \mu m)/Q_{abs}(\lambda = 100 \mu m) = 730$; Draine & Lee 1984), also substantiates the progenitor’s mid-infrared brightness around 2004 reported in Khan (2013).

Once the ZAMS mass is constrained, the models are allowed to evolve with an average mass-loss rate in Dutch scheme (de Jager et al. 1988; Nieuwenhuijzen & de Jager 1990). The enhanced mass-loss rate is triggered by hydrogen stripping and flashes with an upper limit of ∼1 M☉ yr⁻¹ in the last ∼2–3 years of evolution (see Appendix A for details). Any heavy mass loss much before this would move too far away from the star and become too diluted to substantially affect the early light curves of the explosion. We use networks of 21 isotopes during heavy element fusion, and keep an Fe core infall velocity limit of 10⁶ m s⁻¹ as a stopping condition of pre-SN evolution.

Noting that the bolometric luminosity and radius vary with mass-loss rate (Figure 2), we calculate the CSM profile from the history of mass-loss rate, radius, and surface temperature assuming asymptotic wind speed of 10 km s⁻¹. Although the launch velocity was found to vary with mass-loss rate, we assume the ejected gas has had enough time to relax to the asymptotic speed during the episodic ejection. We do not apply any mechanical, hydrodynamic, or thermodynamic interaction between adjacent shells of ejected gas. The only source of thermal evolution is assumed to be adiabatic cooling due to expansion. The chemical composition and electron fraction in CSM are taken to be the same as that of the surface. In contrast to a smooth, continuous, inverse-square radial profile of density, our constructed CSM from the episodic mass loss (see Appendix C) is a collection of discrete shells of non-monotonically varying density (see Figure 3).

Figure 1. Constraint on ZAMS mass of SN 2013ej progenitor using archival images of HST(WFC). Apparent magnitude has been corrected for distance and interstellar extinction using values quoted in Bose et al. (2015) to convert it into absolute magnitude. The error bars represent a composite of error in photometric data and errors in estimation of distance and interstellar extinction. The circumstellar dust extinction for 12–14 M☉, the mass range with color that falls within the observed limit, turns out to be ∼0.7–1.2 mag in V band and ∼0.6–0.8 mag in I band, which clearly implies reddening and circumstellar extinction 3–6 times the average galactic extinction of ∼0.2 mag. Even after dust opacity correction, the I magnitude of 16 M☉ and 19 M☉ calculated by MESA falls outside of the 1σ error bars of the observed magnitude.

Figure 2. Variation in radius (top) and luminosity (bottom), with large mass-loss rate in the late stage of stellar evolution of a model of ZAMS mass 13 M☉.

2.2. Explosion Characteristics

We have stitched the resultant CSM to the progenitor and exploded it via SNEC using a thermal bomb.¹⁰ We have varied the explosion energy in the range of (0.4–1.4) × 10⁵¹ erg in step of 0.2 × 10⁵¹ erg. We fix ⁵⁶Ni mass at 0.0207 M☉ (Valenti et al. 2016) and evenly spread it from outside of the Fe core to the middle of He and C core of each progenitor. After boxcar smoothing this distribution gets modified with a tail extending up to the He core boundary (Figure 3(a)). Because ⁵⁶Ni is injected externally in the simulation, it does not have any velocity distribution appropriate for the explosion. The initial spatial distribution of ⁵⁶Ni over mass coordinate as referred to above is designed in a way such that it can mimic the shocked distribution as found in 3D simulations involving explosive nucleosynthesis (right panel, Figure 6, Wongwathanarat et al. 2017). The mass of the remnant has been taken to be equal to the Fe core mass of each progenitor, which is typically ∼1.4–1.5 M☉. Because the density profile has a steep fall and the velocity profile has a turnover from homologous compression ($v \propto -r$) to gravitational infall ($v \propto -\frac{1}{\sqrt{r}}$) across the boundary of the Fe core, and shock energy is a sensitive function of kinetic energy and gravitational potential energy, we choose the remnant mass carefully. This is in contrast with earlier works, where ⁵⁶Ni is spread up to a constant mass coordinate and the mass of the remnant is also a constant irrespective of the internal structure of the progenitor. The light curves have been calculated until 120

¹⁰Because a thermal bomb and piston produce similar outputs, but the former takes less computational time as pointed out by Morozova et al. (2015), we have used thermal bomb throughout.
days in order to cover a part of the radioactive tail after plateau. The magnitudes in different bands have been calculated using proper bolometric corrections with blackbody approximation.

3. Results

The resultant light curves in g, V, R, I, and z bands have been compared with the data given by Richmond et al. (2014) and Yuan et al. (2016). The reduced error of our SNEC outputs against the data has been defined following Morozova et al. (2017) as

$$
\chi^2_v = \sum_{\lambda \in [g,V,R,I,z]} \frac{1}{\sigma^2_i} \left( \sum_{t} \frac{(m_{\text{obs}}(t, \lambda) - m_{\text{th}}(t, \lambda))^2}{\sigma^2_i} \right) \times \left( \sum_{\lambda \in [g-V]} n_{\lambda} - 5 \right).
$$

Here, $t_{pl}$ is plateau length, which is $\sim 99$ days, $m_{\text{th}} = M_{\text{th}} + ($distance and extinction correction$)$ where $M_{\text{th}}$ is the absolute magnitude returned by SNEC, and $n_{\lambda}$ is the number of data points in a particular band. All sources of errors, i.e., the photometric error in observational data, uncertainty in distance, and extinction estimation, have been included in $\sigma$. We have used the distance and interstellar extinction correction quoted in Richmond (2014), Bose et al. (2015), Huang et al. (2015), and Yuan et al. (2016). We find that for the set of values quoted in Richmond (2014); distance $d = 9.12 \pm 0.84$ Mpc and $A_V = 0.21 \pm 0.04$, the best-fitted model with CSM has ZAMS mass $12-13 M_\odot$ and explosion energy $E_{\text{exp}} = 0.6 \times 10^{51}$ erg, while the values of Yuan et al. (2016) and Bose et al. (2015); distance $d = 9.57 \pm 0.7$ Mpc and $A_V = 0.185 \pm 0.004$ predict best-fitted ZAMS mass $13 M_\odot$ and a range of $E_{\text{exp}} = 0.6-0.8 \times 10^{51}$ erg. Huang et al. (2015) has considered a larger value of extinction by taking the reddening of host galaxy M74 into account. Using their values (distance $d = 9.6 \pm 0.5$ Mpc and $A_V = 0.37 \pm 0.19$) we can pinpoint a ZAMS mass $13 M_\odot$ and $E_{\text{exp}} = 0.8 \times 10^{51}$ erg. The light curves of models without dense nearby CSM deviate from the data with a different distribution (Figure 4); they have a goodness of fit worsened typically by a factor of 2 compared to the light curves of explosions taking place in dense, nearby circumstellar medium (Table 1). We find that the required explosion energy for the progenitors with dense CSM is reduced by almost a factor of 2 compared to the case without any dense and compact CSM. The results have been cross-checked against the data from Richmond (2014), Valenti et al. (2014), and Bose et al. (2015) to confirm that the best-fitted ZAMS mass and explosion energy turn out to be similar to results from the analysis with all of the data sets. We see that the model with CSM best fitted using Huang’s values of the distance and interstellar extinction correction is visually closest to the data (Figure 5). It strengthens the consideration of host extinction, which is confirmed by recent analysis of massive star population around the site of explosion (Maund 2017). Although it was intended to fit only up to the plateau, because SNEC is not reliable beyond that region (Morozova et al. 2015), the model with dense and nearby CSM fits the radioactive tail reasonably well in four (gVRI) bands. Also, the model predicts the peak magnitude in $U$ and $B$ bands correctly. On the other hand, the best-fit model without CSM hardly satisfies any feature of the light curve. From this we can infer that the progenitor of SN 2013ej was very likely to be surrounded by dense, compact, slowly moving nearby CSM that was formed due to enhanced mass ejection in a very late stage of its evolution. This analysis is
consistent with the spectroscopic observations of Bose et al. (2015), where a weak ejecta-CSM interaction was inferred from the high velocity Hα–Hβ profiles.

We also compare our result with earlier works (Morozova et al. 2017) and find that our model (with CSM) better reproduces the data over a longer period. Both models match the early light curves (first ∼20 days) equally well, but the one from Morozova et al. (2017) starts overestimating the light output after ∼50 days. On the other hand, our model reproduces data very well in the whole plateau region, during the transition from plateau to radioactive phase and also in the beginning of radioactive phase (Figure 6).

4. Summary and Discussions

In this paper we have discussed how different mass-loss scenarios for the same ZAMS star can pass through two evolutionary tracks, differing in a timescale much less than the Kelvin–Helmholtz timescale and end up as different pre-SN progenitors, even though they occupy roughly the same position in H-R diagram. The density, velocity, and temperature profiles of the hydrogen envelopes of the stars with no huge mass-loss history are substantially different from those of the progenitors surrounded by dense and compact CSM (Figure 3); even though total mass (envelope + CSM) is the same in both cases. So the rise and plateau of the light curve, which are functions of the hydrogen profile, are expected to be different. In these cases, although the pre-SN images of the progenitor star may not be distinguishable unless the star is very nearby, the light curves of resulting explosions will differ substantially. We note some particular differences due to the presence of dense and compact CSM: (1) UV and optical bands are simultaneously bright in the early phase, and (2) for a fixed shock energy the optical light curve is brighter at peak, flatter after peak, and the plateau is longer. These are consistent with what was noticed and discussed by Moriya et al. (2011) in a simpler scenario with artificially designed smooth and continuous wind approximation. The simultaneous brightness in the NUV and optical can be explained by the recombination and de-excitation of elements in the CSM which are (respectively) ionized and excited by the decelerated shock passing through the CSM. A larger fraction of the shock energy transferred to the dense CSM gets thermalized and eventually diffusively radiated. It brightens the early light curve and flattens the light curve after peak by reducing the adiabatic loss. From the plateau length it is clear that the same hydrogen mass spread over a larger radius contributes more toward the light output. The key difference between this scenario and usual Type II-n SNe is that the extended CSM in Type II-n is optically thin, while here the photosphere lies in the compact CSM for up to ∼40 days from the explosion. In usual Type II-n the interactive phase lasts for ∼1 yr, but in our case the intense interaction happens for ∼2–3 days and the breakout takes place when the shock has already traversed through the dense and compact CSM. The CSM behaves like a gravitationally unbound extended part of the progenitor, but is definitely different from an inflated stellar envelope. Because the lack of detection of early radio emission and flash-ionization in the CSM points to the proximity and compactness by putting constraint on the radial extent of the CSM (Yaron et al. 2017), our assumption of dense and compact CSM is supported by the null radio emission from SN 2013ej in an early very long baseline interferometry (VLBI) observation by Sokolovsky et al. (2013).

We also carefully account for extinction in the pre-SN stage and show how the dust opacity can affect the pre-SN images. Unless calculated correctly, this may lead to incorrect inferences of the properties of the progenitor, which can get propagated into further analysis. The CSM which contributed in supernova light curves did not need any similar opacity corrections. Before the explosion, the dense circumstellar material could not move far away from the star to cool down to form dust steadily. Also, when the shock comes out of the star and hits the CSM it deposits a larger fraction of its energy to the CSM, part of which heats up the CSM. This will sublimate all of the dust even if it is formed earlier.

Along with confirming earlier studies (Moriya et al. 2017; Morozova et al. 2017) that nearby wind-like circumstellar material indeed affects early light curves of SNe, we show that the late-time enhanced mass ejection can result in such dense and nearby CSM. Our method and results support the suggestion and explanation by Quataert & Shiode (2012), Smith & Arnett (2014), Moriya (2014), and Fuller (2017) that the mass-loss rates of red supergiants increase by several orders of magnitude prior to the SN explosion. There are different mechanisms proposed to explain late-stage mass-loss enhancement based on the increase in nuclear power in the core. The basic principle is the generation of a vigorous convective motion leading to internal gravity waves carrying energy from
Intermediate II-P and II-n SNe. We argue that the better performance of our model indicates that the light curves depend on the profile of CSM and the progenitor, and hence our approach of letting the star pass through the phase of increased mass-loss rate and constructing CSM from that stellar history is physically reasonable. We note the in-phase change in radius and bolometric luminosity with heavy mass-loss rate (e.g., Figure 2). This indicates that pulsation may have connections with late outburst and eruptions that are not usually included in standard stellar evolution codes. Ideally, the simulation should allow the star to naturally lose mass at any rate depending on a particular phase of post-MS evolution. The combination of the impact of mass-loss variation on the star and the CSM formed as a consequence leads to a detailed profiling of the explosion input. Sampling a range of parameters related to mass loss and advanced modeling of the compact and nearby CSM might help to explain the qualitative similarity of Types II-P and II-L SNe, and the finer details of spectral output of each category; these questions are under investigation.

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Software: MESA-r8118 ( Paxton et al. 2011, 2013, 2015), SNEC v1.01 (Morozova et al. 2015), GNUPLOT v4.6.

Appendix A
MESA Input Models

A sample inlist of the post-MS evolution is shown below. If not explicitly mentioned, all other parameters have been kept at their default values.

```
star_job
! start a run from a saved model
load_saved_model = .true.
saved_model_name = '13Mz0.006.mod'
history_columns_file = 'history_columns_postMS.list'
profile_columns_file = 'profile_columns_postMS.list'
!nuclear reaction network
adv_net = 'approx21.net'
! end of star_job namelist
& controls
```

Table 1
Overview of Progenitor and Explosion Properties Best-fitted for SN 2013ej

| ZAMS mass (M_☉) | Pre-SN CSM mass (M_☉) | Pre-SN CSM radius (R_☉) | CSM mass (M_☉) | CSM radius (R_☉) | Energy (10^{51} erg) | Goodness of Fit (χ^2) |
|-----------------|-----------------------|-------------------------|----------------|----------------|---------------------|----------------------|
| 13              | 11.602                | 0.964                   | 667            | 1650           | 0.6–0.8             | 0.0013–0.0014        |
| 13              | 12.566                | ...                     | 617            | ...            | 1.0–1.2             | 0.0027–0.0031        |

Notes.

a Lost mass during enhanced mass loss rate in last few (~2–3) years.
b The external radius of the dense CSM formed in the last few years before explosion.
c Asymptotic energy of the shock after breakout.
d $^{56}$Ni mass was kept fixed at 0.0207 $M_☉$ (Valenti et al. 2016).
e The range of explosion energy corresponds to the range of $\chi^2$, which is treated as a region of valley instead of a single point of minima because of almost same $\chi^2$ value over the range of energy. Note the better goodness of fit for the first row of the table.

Figure 5. The near-ultraviolet (NUV) (U)-optical (BgVR)-NIR (Iz) light curves of SN 2013ej (data: Yuan et al. 2016). The curves for the best-fitted model (fitted against gVR/Iz bands until the plateau of ~99 days) with CSM are shown with the errors at each point. Values of distance and extinction estimation have been taken from Huang et al. (2015), with relative extinction relation borrowed from Cardelli et al. (1989). Our best-fitted model without CSM is shown in dashed lines for the sake of comparison.

Figure 6. Comparing our work with Morozova et al. (2017) against optical (gVR) and NIR (Iz) light curves of SN 2013ej (data: Yuan et al. 2016). Note how our work differs from their result after ~50 days and better represents the data.
α_{\text{mix}} is the mixing length parameter, \( f_{\text{ov}} \) and \( f_0 \) are exponentially decreasing overshooting parameters (both for the core and the convective shells), and \( \alpha_{\text{sc}} \) is the semi-convection efficiency. We do not change the default option of thermoaline mixing.

Because episodic mass-loss mechanisms are not incorporated into the code, the stellar evolution is artificially halted at different points by using a different value of maximum age of our choice that is less than the lifetime of the star, and thus the mass-loss rate can be tuned in selected intervals. Instead of running a grid of the *enhanced mass loss rate* and its *duration*, we have considered possible constraints on the *duration of the enhanced mass loss* (duration \( \sim \) the difference of age at final core-collapse and the initiation time of the mass-loss enhancement). The former two are in some ways coupled and together have substantial effects on the SN light curves when the progenitor star explodes. Because the luminosity of the star goes up with mass-loss increase, and Fraser et al. (2014) has progenitor observations until 2008 without any trace of remarkable increase in brightness, the enhanced mass loss could not have taken place more than 5 years before the final collapse. Moreover, the null result from early radio observations by Sokolovsky et al. (2013) suggest that the dense CSM, if it exists, should be compact and close to the progenitor. Now, most of the predictions of late-stage mass-loss enhancement are based on the increase in nuclear energy production rate (Quataert & Shiode 2012; Moriya 2014; Fuller 2017). Therefore, we try to relate the *duration of the enhanced mass loss* with the time when two major reactions, the \(^{16}\text{O} \) and \(^{28}\text{Si} \) burning stages, dominate energy production. In Figure 7 we see that for 12–14 \( M_\odot \) (ZAMS) stars, the energy production rate becomes more than 75% of total nuclear luminosity \( \sim 2.5–4.5 \) years before the final collapse, which suggests that the mass loss should become enhanced around this timescale. We tried mass-loss enhancement 1 year before the collapse, but the actual mass-loss rate never became as high as 1 \( M_\odot \) yr\(^{-1} \) even though the upper limit was increased to \( \sim 3–10 M_\odot \) yr\(^{-1} \). This is probably because this timescale is not enough for the star to jump to a high mass-loss rate (\( \sim 1 M_\odot \) yr\(^{-1} \)) and relax back to equilibrium. We then chose mass-loss enhancement 2–3 years before the collapse, which worked satisfactorily. So, choosing other values of the *duration of the enhanced mass loss*, after taking into account of all of the constraints stated above, would only change the final progenitor profile by a factor of few, if at all.

Apart from the usual schemes of standard mass loss, hydrogen stripping and flashes are two ways to artificially trigger any change in mass loss. In the case of hydrogen stripping, hydrogen is ejected (i.e., “stripped”) from the envelope with large momentum. In MESA one can only put an upper limit on the rate of mass loss, and the hydrogen stripping goes on until some stopping conditions are met. On the other hand, flashes can emit the mass in a shorter timescale, which is usually in the same order of the temporal resolution of the particular model, and can reach the limit of mass loss mentioned by the user. Because the physical explanation of the enhancement in the late-stage mass loss of massive stars is still debatable, the proposed mechanisms in the literature are not incorporated in MESA. The commands mimic the effect of outbursts/flare observed in late stages of stellar evolution. Smaller values (0.01 \( M_\odot \) yr\(^{-1} \)) have been tried \( \sim 15–20 \) years before the final collapse in order to study the opacity effect of dust in the CSM. To study the effect of dense and compact CSM on the early light curves of SNe, larger values of mass-loss rate (1.0 \( M_\odot \) yr\(^{-1} \)) were triggered. We consider 1 \( M_\odot \) yr\(^{-1} \) as an order of magnitude estimate of high mass-loss rate. Because this is an upper limit and not the exact value, few multiples or fractions of it would not necessarily lead to a noticeably different mass-loss history and, consequently, a different CSM profile, and therefore would not change the SN light curves substantially when the shock interacts with the dense circumstellar medium. Because this enhancement continued only for 2–3 years, we did not put any lower limit of hydrogen mass as a stopping condition.

Near the center of the star mass, resolution is increased by three times the default value.

The “photostep” is reduced to a small value in order to save the intermediate models at smaller time intervals, so that the evolution can be restarted with a new set of parameters from any instant.
We took the following approximations and corrections:

1. From the composition of the surface of the star, we find that only graphite dust can be formed in the CSM. We assume that 50% of the total 12C has formed dust. The density of dust grains ρ_dust has been kept fixed at the average value of 2.26 gm/cc.

2. Because MESA is a 1D calculation, the angle-dependent Q_{abs}(a, ν) of Equation (2) has been neglected.

3. Because the CSM is close to the star and hence illuminated by the stellar radiation, we take β = 1.81 (Equation 3) from Perna et al. (2003). This is different from the galactic value of 3.5 under an undisturbed medium approximation.

4. Because under the influence of radiation larger dust grains fragment into smaller ones and a portion of smaller grains evaporate, the range of grain radius “a” (Equation 2) evolves. We have considered the asymptotic distribution of a_{max} = 0.22 μm and a_{min} = 0.15 μm with normalization constant A modified to 0.00045 × A (see Equation 3), signifying a reduction in the total number of dust particles.

5. In the abovementioned range of grain radius, we see from Figure 4(a) of Draine & Lee (1984) that the coefficient of absorption Q_{abs}(a, ν) is independent of “a.” Considering the frequency range of Johnson’s B, V, and I bands we find Q_B = 1.4, Q_V = 1.5 and Q_I = 1.0.

6. We convert the number density (n_H) into mass density (ρ_H) and express the radial integration of Equation (2) in terms of distance covered by the wind. Thus, the integral becomes a direct function of the parameters related to mass loss: mass-loss rate, wind speed, duration of mass loss, etc., which has been read and used from MESA outputs.

7. Because the dust destruction temperature is T_d = 1500 K, R_{min} is chosen at a point where the temperature falls below T_d. We have assumed a simple adiabatic cooling of the wind due to expansion.

We find that the extinction at a particular time of observation not only depends upon (a) the total mass lost, but also on (b) the duration of mass loss and (c) the instant of mass loss. First, the lost mass should have enough time before observation to move away from the star and cool below the dust destruction temperature, but should not move so far away that it becomes too dilute to contribute in the extinction. Second, the duration of mass loss will control the compactness and radial profile of the CSM density, upon which extinction is strongly dependent. An optimized combination of mass-loss rate and these two parameters can give the required extinction. We tuned these three variables in MESA and found that for two episodes of mass loss, roughly 1.5–2.0 years duration, and with an upper limit of ~0.01 M_⊙ yr^{-1}, one of which occurred ~15 years before final collapse (i.e., ~5 years before the 2003 HST observation)
and another that occurred \(\sim 10\) years before collapse (i.e., between 2003 and 2005), a CSM is formed with a mass of \(\sim 0.05\) \(M_{\odot}\) spread over \(\sim 1000\) \(R_{\odot}\). This can give rise to an extinction of 0.7–1.2 mag in \(V\) band. We attribute the mass loss enhancements to small pulsation (\(<1\%\) \(R_{\odot}\)) and the increase of\(\text{Ne} + \text{Na} + \text{Mg}\) burning power (see Figures 8 and 9), as found from MESA outputs.

**Appendix C**

**Construction of Circumstellar Profile**

We have constructed the CSM similar to conventional RSG winds. The density of an ejected shell of gas is defined as

\[
\rho_{\text{wind}} = \frac{\dot{M}}{4\pi v_{\text{wind}}^2}. \tag{4}
\]

In our work \(r = v_{\text{wind}} \times t + R_{\text{star}}(t)\), “\(t\)” is the time before final collapse, and \(R_{\text{star}}\) is the radius of the star when the gas was ejected. We assume that the gas is emitted from the surface of the star. So in a given MESA output, where the variables were the upper limit of mass-loss rate and the duration of the enhanced mass loss, we do not have any free parameter as such. The external radius of the CSM \(R_{\text{ext}}\) is primarily determined by the maximum value of “\(t\)”, such that \(\rho_{\text{wind}}\) does not fall below \(\sim 10^{-11}\) g cm\(^{-3}\), i.e., \(\sim 1\%\) of the stellar surface density. The maximum value of “\(t\)” is in the order of the duration of the enhanced mass loss. Since \(\dot{M}\) is a time-dependent variable in our simulation, and \(R_{\text{star}}\) was found to vary with \(\dot{M}\) (see Figure 2), the density profile depends strongly on the history of mass loss and surface properties of the star, and does not follow any constant integer-power radial dependence, as opposed to the assumption of Moriya & Tominaga (2012) and Moriya et al. (2017; see Figure 3). Although the surface temperature \((L = 4\pi R_{\text{star}}^2 \sigma T^4)\) hardly changes during the period of episodic ejection, the temperature profile of the CSM does not remain smooth or constant because of its radial dependence. Because temporal resolution was increased during enhanced mass loss, the enclosed mass in CSM is calculated as \(M = \sum \dot{M}(t) \times \Delta t\), using the simple trapezoidal rule. We had \(\sim 260\) data points to sum over \(\sim 2–3\) years.

**Appendix D**

**Explosion Parameters in SNEC**

The final profile of our MESA models have been fed as inputs of SNEC. Because the convention of indexing cells in SNEC is opposite from that in MESA (from surface to center), the outputs of MESA have been flipped and arranged in a format compatible with SNEC before use. Here we actually skip the intermediate detail of the core bounce and formation of shock. The calculation in SNEC starts from the moment when the shock has gained enough energy to come out of the infalling matter of the star and has begun its final outward propagation through the rest of the star. The main explosion parameters used here in SNEC are explosion energy, \(^{56}\text{Ni}\) mass and its spread over mass coordinate, and the mass of the remnant, which would eventually turn into a neutron star or black hole. The explosion energy is the asymptotic energy of the shock once it comes out of the stellar ejecta and CSM in the vicinity, if any. Because SNEC always assumes a successful explosion, the initial shock energy is calculated as the...
sum of binding energy (kinetic+ internal+ gravitational energy of the stellar material that the shock will pass through) and user-given explosion energy. Radioactive $^{56}\text{Ni}$ is artificially injected to mimic the effect of explosive nucleosynthesis. $^{56}\text{Ni}$ mass reflects the slope of the exponential tail after plateau. Its spread over the stellar mass determines how fast it would be exposed to the photosphere and directly contribute in the optical light curves. SNEC does not account for any post-shock fallback mass, so the mass coordinate from where the shock begins moving outward is equal to the mass of the remnant. For a given stellar model, we have varied explosion energy only. The detail of how other parameters are chosen is mentioned in Section 2.2.

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