The first and second mass eruptions from progenitors of Type IIn supernovae: Is there any difference?

Naoto Kuriyama1 and Toshikazu Shigeyama2

1 Research Center for the Early Universe, Graduate School of Science, University of Tokyo, Bunkyo-ku, Tokyo, Japan
2 Department of Astronomy, Graduate School of Science, University of Tokyo, Bunkyo-ku, Tokyo, Japan

Received XXX / Accepted YYY

ABSTRACT

Context. Some massive stars experience episodic and intense mass loss phases with fluctuations in the luminosity. Ejected material forms circumstellar matter around the star, and the subsequent core-collapse results in a type IIn supernova which is characterized by interaction between supernova ejecta and the circumstellar matter. The energy source which triggers these mass eruptions and dynamics of the outflow have not been clearly explained. Moreover, the mass eruption itself can alter the density structure of the envelope and affect the dynamics of the subsequent mass eruption if these events repeat. In fact, a large amount of observational evidence suggests multiple mass eruptions prior to core-collapse.

Aims. We investigate the density structure of the envelope altered by the first mass eruption and the nature of the subsequent second mass eruption event in comparison with the first one.

Methods. We deposited an extra energy twice at the bottom of the hydrogen envelope and calculate the time evolution by our radiation hydrodynamical simulation code. We do not deal with the origin of the energy source but focus on the dynamics of repeated mass eruptions from a single massive star.

Results. There are significant differences between the first and second mass eruptions in terms of the luminosity, color, amount of produced circumstellar matter. The second eruption leads to a redder burst event with the associated brightening phase lasting longer than the first one. The amount of ejected matter is different even with the same deposited energy in the first and second event, but the difference depends on the density structure of the progenitor star.

Conclusions. Upcoming high cadence and deep transient surveys will provide us a lot of detailed pre-supernova activities, and some of them would show multi-peaked light curves. They should be interpreted taking the effect of density structure altered by the preceding outburst events into consideration.

Key words. stars: massive - stars: mass-loss - supernovae: general

1. Introduction

Growing observational evidence suggests that massive stars sometimes experience episodic and intense mass loss accompanied by temporal brightening. Eta Carinae is one of the most well-studied and well-known objects which experienced such events (e.g., Davidson & Humphreys 1997). This intense mass loss or brightening event has been considered to be related with the activity of luminous blue variables (LBVs), which were introduced by Conti (1984). On the other hand, some recent observations suggest that Wolf-Rayet stars (WR stars) may also experience such events (Foley et al. 2007, Pastorello et al. 2008, Smith et al. 2020).

When an intense mass loss takes place, dense circumstellar matter (CSM) is formed around the star. If a core-collapse supernova (SN) takes place in this dense CSM, the expanding SN ejecta collide with the CSM. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta. The kinetic energy of the ejecta is dissipated at shocks and becomes the main energy source of the SN ejecta.

Recent observations reveal that some progenitors of SNe IIn actually experienced temporary brightening phase a few or a few years before the core-collapse. For example, SN 2018cnf (Pastorello et al. 2019), SN 2016bdu (Pastorello et al. 2018), SN 2013gc (Reguitti et al. 2019), PTF12cxj (Ofek et al. 2014), and SN 2011ht (Fraser et al. 2013) were reported to exhibit such brightening. Since the peak luminosity exceeds the Eddington luminosity of a massive star, this brightening must lead to an eruptive mass loss. The sparsely observed light curves prior to these SNe show that the brightening phase typically lasted for several years and indicate that the progenitors repeated episodic mass loss events during this period. SN 2009ip (Soker & Kashi 2013, Mauerhan et al. 2013, Pastorello et al. 2013, Smith et al. 2014, Graham et al. 2017) is one of the most famous SNe IIn whose progenitor star had experienced multiple brightening phases likely associated with episodic mass loss events. The progenitor of SN 2009ip in a brightening phase was first detected in 2009, and repeatedly exhibited brightening with short intervals less than 50 days (Pastorello et al. 2013) in 2011. Eventually it experienced the most luminous outburst “2012b” in 2012 which is thought to be a genuine supernova.

The mass loss rates from progenitors of SNe IIn are estimated at 0.026 ÷ 0.12 M⊙ yr⁻¹ (Kiewe et al. 2012), 10⁻⁴ ÷ 10⁻² M⊙ yr⁻¹ (Taddia et al. 2013) or more than 10⁻³ M⊙ (Moriya et al. 2014). These values are so high that they cannot be recon-
cled with a steady wind mass loss model like Vink et al. (2001); van Loon et al. (2005); Smith (2014). In addition, some SNe IIn show bumps in their light curves which are thought to be related to bumpy density structures of CSM (Reguitti et al. 2019; Nyholm et al. 2017; Stritzinger et al. 2012). Although they seem to be the rare cases among SNe IIn (Nyholm et al. 2019), this bumpy CSM structure also implies not steady but episodic mass loss events from the progenitor star. Therefore, a dynamical phenomenon, which is not included in most of current stellar evolution models, would occur during the temporary brightening phase.

Although there is a plenty of observational evidence of intense mass loss as described above, the extra energy source which triggers the intense mass loss has not been fully understood. There are two types of scenarios explaining the extra energy source: energy supplied from nuclear burning and/or core convection (Woosley et al. 2007; Woosley & Heger 2015; Woosley 2017; Quataert & Shiode 2012; Shiode & Quataert 2014; Smith & Arnett 2014; Mocak et al. 2018; Yadav et al. 2020; Soker & Gikiš 2017; Moriya 2014) and energy originating from binary interaction (Smith 2011; Mcley & Soker 2014; Danieli & Soker 2019). We focus on the former type and consider a single star assuming that the extra energy is supplied from violent nuclear burning. The energy generation rate of nuclear burning in a massive star increases with time and reaches at a local peak about ten years before core-collapse (Fig. 1) depending on the core mass. We assume this local peak is related to an intense mass eruption (Sect. 2).

As well as considering an extra energy source, it has been also discussed in previous research how the extra energy is transported towards the stellar surface and what kind of observational feature emerges. Quataert et al. (2016), Fuller (2017), Fuller & Roj (2018), and Ouchi & Maeda (2019) investigate how the envelope responds to an extra energy injected continuously at a super-Eddington rate. Dessart et al. (2010), Owociki et al. (2019), and Kuriyama & Shigeyama (2020) consider the dynamical eruptive mass loss event when an extra energy is deposited at the bottom of the envelope with a short timescale. In these researches, energy is deposited only once and the corresponding single dynamical eruption event is discussed. However, intense mass loss event often repeats in the real situation as discussed above and this could become a key factor for understanding the mass loss mechanism. Once a dynamical eruption takes place, the expanding envelope will keep its altered density profile for the thermal time scale. If another eruption event occurs again before the density profile relaxes and returns to the hydrostatic state, the property of the second eruption may be completely different because of a different density profile of the envelope. To deal with this problem, we study dynamics of eruptive mass loss which repeats twice. Of course eruption can repeats more than twice, we focus on a comparison between eruptions from the original (hydrostatic) envelope and the expanding envelope in this work.

In this study, we investigate intense and eruptive mass loss from progenitors of SNe IIn. We assume that eruptive mass loss is related to the local peak of the energy generation rate of nuclear burning shown in Figure 1 although the specific mechanism of energy transportation from the burning region to the envelope is not assumed. We deposit an extra energy at the bottom of the hydrogen envelope twice and investigate the properties of each eruption and difference between the first and second eruptions. The second energy injection is conducted before the stellar envelope relaxes from the first injection. Each extra energy is injected for a short period of time and the resulting dynamical eruption is investigated by radiation hydrodynamical simulations. In Sect. 2, we introduce the progenitor models which we use as initial models in our simulation and the method of radiation hydrodynamical calculation. In Sect. 3 we present the results of calculation and find out differences between the first and second eruptions. We clarify implications to observations in Sect. 4 and present conclusion in Sect. 5.

2. Set up and Methods

2.1. Progenitor models

Although it has been often considered that eruptive mass loss and SNe IIn are related to activities of LBVs (e.g., Gal-Yam et al. 2007; Langer 2012) as described in Sect 1, observations suggest that red supergiants (RSGs) may also be progenitors of SNe IIn (Smith et al. 2009; Bilinski et al. 2015). Thus, we adopted two types of progenitors in this study, namely, blue supergiant model (model BSG) and red supergiant model (model RSG). We made these progenitor models using a stellar evolution code MESA (Paxton et al. 2011; 2013; 2015; 2018; 2019). We stop the calculations of MESA 11.2 yr before core-collapse for model RSG.

![Fig. 1. Evolution of the energy generation rate by nuclear burning for each model indicated by labels. The rate becomes higher towards the core-collapse. There are some local peaks for each model around ten years, five years, and one year before core-collapse. We adopted the peaks at 11.2 years before core-collapse (model RSG) and at 7.2 years before core-collapse (BSG) as initial models for our calculations. These peaks correspond to core neutron burning phase.](image1)

![Fig. 2. Density distribution of each progenitor model. Model RSG has a more extended envelope than model BSG because of higher metallicity (Table 1) and opacity. In addition to that, model RSG has experienced stronger mass loss due to higher metallicity and thus has a lower total mass.](image2)
Table 1. Properties of two SNe Progenitor models.

| Model | $M_{ZAMS}$ | Z | R | $T_{\text{eff}}$ | $M_{\text{He, core}}$ | $M_{\text{He, env}}$ | $E_{\text{envelope}}$ | Time to CC | Burning stage |
|-------|------------|---|---|-----------------|------------------------|----------------------|----------------------|------------|---------------|
| RSG   | 15$M_\odot$ | 0.02 | 696$R_\odot$ | 3500K | 4.1$M_\odot$ | 10.6$M_\odot$ | $-5.6 \times 10^{47}$ erg | 11.2 yr | Ne burning |
| BSG   | 15$M_\odot$ | 0.0002 | 76$R_\odot$ | 10200K | 4.2$M_\odot$ | 10.8$M_\odot$ | $-1.7 \times 10^{49}$ erg | 7.9 yr | Ne burning |

Notes: Total energy of H-rich envelope

Table 2. Amount of injected energy $E_{\text{inj1}}, E_{\text{inj2}}$ and time when a injection begins $t_{\text{inj1}}, t_{\text{inj2}}$. Two patterns of calculations were conducted for each model (Totally four patterns of calculations).

| Calculation model | Progenitor model | $t_{\text{inj1}}$ | $E_{\text{inj1}}$ [erg] | $t_{\text{inj2}}$ | $E_{\text{inj2}}$ [erg] |
|-------------------|------------------|-----------------|---------------------|-----------------|---------------------|
| RSG1              | RSG              | 0 s             | $1.5 \times 10^{47}$ | 98 day          | $1.5 \times 10^{47}$ |
| RSG2              | RSG              | 0 s             | $1.5 \times 10^{47}$ | 98 day          | $3.0 \times 10^{47}$ |
| BSG1              | BSG              | 0 s             | $6.0 \times 10^{48}$ | 3.1 $\times 10^{5}$ s | $6.0 \times 10^{48}$ |
| BSG2              | BSG              | 0 s             | $6.0 \times 10^{48}$ | 3.1 $\times 10^{5}$ s | $9.0 \times 10^{48}$ |

Fig. 3. Light curves for models RSG1 and RSG2. The first (the second) eruption, triggered by the injected energy $E_{\text{inj1}}$ ($E_{\text{inj2}}$), produces a peak at day ~ 80 (~ 230).

2.2. 1-D Radiation Hydrodynamical Simulation

As described in Sect. 1, the main purpose of this paper is revealing differences in the properties between the first and second mass eruptions from SNe IIn progenitors. To investigate this topic, we used the same 1-D radiation hydrodynamical simulation method as in Kuriyama & Shigeyama (2020). We injected an extra energy into the bottom of the hydrogen envelope twice without specifying from where and how the extra energy is supplied (the mechanism for supplying the extra energy has not been fully understood so far, see Sect. 1). For model BSG, the time-interval between the first and the second energy injection was chosen to reproduce repeated mass eruption events with short intervals (less than 30 days) observed for SN 2009ip (Pastorello et al. 2013). This time interval (3.1 $\times 10^{5}$ s, see Table 1) is just equal to the dynamical timescale of the BSG progenitor model made by MESA. To compare with model BSG, the time-interval between two energy injections for model RSG was set to the dynamical timescale of the RSG progenitor model, which corresponds to ~ 98 day. According to Table 2, the first energy $E_{\text{inj1}}$ was injected at the time $t_{\text{inj1}}$ and the second energy $E_{\text{inj2}}$ was injected at $t_{\text{inj2}}$.

3. Results

3.1. First energy injection and corresponding mass eruption

Two injections of extra energies at different epochs cause two distinct mass eruption events (Table 3) and two distinct peaks of luminosity (Fig. 3). About one quarter (model RSG1,2) or one third (BSG1,2) of $E_{\text{envelope}}$ is injected into the bottom of the hydrogen-rich envelope in the first energy injection $E_{\text{inj1}}$. A relatively strong shock wave propagates towards the surface and breaks out with a rapidly rising light curve in all the models. The first energy injection ejects matter with masses of ~ 0.01$M_\odot$ (model RSG1,2) and ~ 0.2$M_\odot$ (model BSG1,2) (Ejected mass in model RSG1 and RSG2 (model BSG1 and BSG2) are equal in the first eruption because the same amount of energy $E_{\text{inj1}}$ is injected.). Although the ratio of $E_{\text{inj1}}/E_{\text{envelope}}$ for model RSG1,2 is similar to that for model BSG1,2, there is an order of mag-
Table 3. Amount of ejected mass for two distinct mass eruption events corresponding to the first and the second energy injection.

| model | First eruption" | Second eruption |
|-------|-----------------|----------------|
| RSG1  | 0.013\(M_\odot\) | 0.0015\(M_\odot\) |
| RSG2  | 0.73\(M_\odot\)  | 0.5\(M_\odot\)   |
| BSG1  | 0.19\(M_\odot\)  | 0.51\(M_\odot\)  |
| BSG2  | 2.02\(M_\odot\)  | 2.02\(M_\odot\)  |

Notes. RSG1 and RSG2 (BSG1 and BSG2) eject the equal mass in the first eruption because the same amount of energy \(E_{\text{inj1}}\) is injected.

Fig. 4. Light curves for model BSG1 and BSG2. The first (the second) eruption, triggered by the injected energy \(E_{\text{inj1}}\) (\(E_{\text{inj2}}\)), produces a peak at day \(\sim\) two (\(\sim\) 15).

Fig. 5. Evolution of effective temperature for each RSG progenitor model.

Fig. 6. Evolution of effective temperature for each BSG progenitor model.

Fig. 7. Radii as functions of the enclosed mass for all the models. The three lines in each panel represent the profiles before the first energy injection (dotted line), between the first and the second energy injections (dashed line), and at the end of the hydrodynamical simulations (solid line).

magnitude difference in the ejected mass above. This is because the envelope of model BSG is denser than that of model RSG and therefore a more energetic shock wave propagates outwards and expels a considerable amount of the envelope. For both models RSG1,2 and BSG1,2, the hydrogen-rich envelopes remain
3.2. Second energy injection and corresponding mass eruption

Before the expanding envelope shrinks and returns to a hydrostatic state, the second energy injection is conducted. The amount of injected energy is the same as in the first injection for model RSG1 and BSG1. On the other hand, for models RSG2 and BSG2, twice (model RSG2) or 1.5 times (model BSG2) more energies are injected. These second energy injections trigger the second mass eruption events accompanied with the second peaks in luminosity. The matter ejected by the second energy injection collides and interacts with the expanding envelope or matter ejected by the first energy injection.

There are three key differences between the first and second mass eruptions. First, the brightening phase associated with the second mass eruption lasts more than ten times longer than that in the first mass eruption (Fig. 3 and 4). The luminosity gradually increases because photons can easily diffuse out from the shock wave in the inflated low-density envelope. After the peak, the luminosity slowly declines and the brightening phase lasts \(\sim 100\) days in model RSG1,2 and \(\sim 10\) days in model BSG1,2.

Second, there is a significant difference in the color between the first and second mass eruption events (Fig. 5 and 6). For every model, when the first mass eruption takes place, its effective temperature rises by a factor of \(\sim 10\). On the other hand, in the second mass eruption, the effective temperature rises but does not reach 10,000 K. The temperature at the local maximum in the second mass eruption is even lower than the effective temperature of the original state before the first energy injection (namely the output value from MESA). Thus a progenitor star...
observed a few years before the supernova does not necessarily follow the standard core mass luminosity relation constructed by the standard stellar evolution models which assume quasi-hydrostatic evolution.

Third, the amount of ejected mass is different between the first and second mass eruption even with the same injected energy ($E_{\text{inj}} = E_{\text{inj}}$ for RSG1 and BSG1). Interestingly, RSG1 and BSG1 show the opposite results. While the second energy injection ejects ~ 2.5 times larger mass than the first injection in model BSG1, it ejects only one-tenth mass of the first injection in model RSG1. These results come from two antagonism effects, which are the weakly bound envelope after the first eruption (this effect enhances eruption) and shock wave attenuation due to diffusion of photons (this effect weakens eruption). While the latter effect works in model RSG1, the former one works stronger in model BSG1.

In model RSG2, the second energy injection ejects ~ 5 x $10^2$ times larger mass than that in model RSG1 even though the difference of $E_{\text{inj}}$ between them is only a factor of two. This result implies that, although there are wide diversity of observed SNe IIn or II-P in terms of the presence or the amount of CSM, there may be smaller difference in the late phase progenitor evolution and extra energy supply between them than it has been thought.

Each ejected fluid element which has a positive total energy (summation of thermal, gravitational, and kinetic energy) keeps expanding at an almost constant velocity until core collapse of the star and SN ejecta-CSM interaction. Erupted material reaches ~ 2 x $10^{15}$ cm (RSG1,2) or ~ 3 x $10^{16}$ cm (BSG1,2) from the progenitor when the star undergoes core collapse. Their velocities are several 10$^6$ cm s$^{-1}$ (RSG1,2) or several 10$^7$ cm s$^{-1}$ (BSG1,2) (Fig. 10). These values do not contradict with observations (e.g., Kiewa et al. 2012). When we express the velocity-density relation in Fig. 10 as $\rho \propto v^{-4}$, the CSM formed by the first eruption (broken line) have larger $v$ values compared with that by the second eruption (solid line), which roughly follow a line with $s \sim 1.5$. This is because a part of photons diffusing out from the shock wave formed by the second eruption can be absorbed and accelerate the inner part of the CSM formed by the first eruption. This "steepening" of $s$ value from ~ 1.5 (and resulting CSM) can affect the light-curve of SNe powered by CSM interaction modeled by Chevalier (1982).

4. Discussion

Our results show unambiguous differences between the first and second mass eruption in terms of light curves, colors, and amounts of erupted unbound mass. Therefore when we discuss the observation of pre-CCSN mass eruption events and compare them with some physical models or simulations, we may have to take the effect of repeated mass eruptions seen in our simulations and the altered density profile of the envelope into consideration. Here we present some implications for the interpretation of recently observed transient events.

The motivation of this work is interpreting the nature of multiple mass eruption events accompanied by rapid and repeated luminosity variance like erratic pre-CCSN phase of SN 2009ip during 2011 March-November. The photometric observations show magnitude oscillation with an amplitude of ~ three mag within the range of $R \sim 17 - 20$ (Pastorello et al. 2013). The period of this luminosity oscillation is less than 50 days and this phase lasts about 10 months. The peak magnitudes in R-band and the time interval of each local peak are almost constant during this erratic phase. On the other hand, in our work, once the first mass eruption occurs, the density structure of the envelope is altered. Thus the local peak luminosity and color are significantly different between the first and second mass eruption (Fig. 3, 4, 5 and 6) although the same amount of energy is deposited on the same time scale (model RSG1 and BSG1). In addition, our models failed to reproduce the fast declining of the luminosity after the second local peak because of the extended envelope. From these view points, our results suggest that the nature of mass eruption from SN 2009ip in 2011 cannot be explained by the spherically symmetric eruption of a single star triggered by extra energy supply into the envelope, although there is a room that asymmetric eruption in 2D or 3D simulation or binary interactions can explain it.

Observations have revealed the diversity of SNe IIn (Taddia et al. 2013, Smith 2017) in the amount of CSM. While some progenitors hold more than 20$M_\odot$ (SN 2016aps, Nicholl et al. 2019) or 30~50$M_\odot$ (SN 2010jl, Zhang et al. 2012) or 20$M_\odot$ (SN 2006gy, Smith et al. 2010) of CSM, others hold only 0.003$M_\odot$ (SN 1998S: Fassia et al. 2001) or less than 0.1$M_\odot$ (SN 2005gl, Gal-Yam & Leonard 2009). This variety could originate from different mechanisms of eruption to form CSM and of course from different progenitor mass. As introduced in Sect. 1, there are a wide variety of scenarios that may explain extra energy supply and resulting mass loss and CSM formation. On the other hand our results show that only a factor of two difference in the amount of deposited energy results in a difference of ejected mass by more than two orders of magnitude (the second mass eruption in RSG1 and RSG2, Table 3). Thus a wide range of the amount of CSM might also reflect small difference in the amount of extra energy supplied and the number of eruption events.

When we compare the results of model RSG and BSG, we find that model BSG requires more than ten times larger amount of energy than model RSG to eject the same mass (both of model RSG2 and BSG1 expel ~ 0.7$M_\odot$ throughout double eruption events). From this aspect, model RSG (i.e., stars in a relatively metal rich environment) is preferred as progenitors of SNe IIn if we focus on only the envelope density stratification and ignore the metallicity dependence of the physics involved in the extra energy injection. At a glance, our results seem to be consistent with Graham (2019), which suggests that SNe IIn prefer relatively higher metallicity environment compared with the other
subtypes of SNe II based on a database analysis work. However, there should be various physical factors which are correlated with metallicity and affect the classification of a (sub-)type of an SN. Therefore our result that metal rich star seems to easily suffer from mass ejection is just one of the possible factors which determine the environment to whom SNe IIn prefer.

5. Conclusions

We have carried out radiation hydrodynamical simulations to investigate the properties of the repeated dynamical mass ejection events from a single massive star prior to the core-collapse, in the context of formation of circumstellar matter (CSM) around SNe IIn. The key point of this work is that we caused mass ejection events not only once but twice by depositing energy two times. The dynamical properties of single mass ejection event have been already studied by [Kuriyama and Shigeyama 2020, Owocki et al. 2019, Dessart et al. 2010]. However, recent observations of SN IIn progenitors indicate that mass ejection phase often occurs more than once just before core-collapse. A mass ejection event can alter the density structure of the envelope and therefore the subsequent mass ejection event can show different observational feature. From this view point, we deposited the extra energy into the bottom of the progenitor envelope twice and simulated the time evolution of both ejection events. The progenitor models were made by MESA. We did not deal with the origin of extra energy which has not been completely understood so far, although it should be studied in our future work.

Results show nonnegligible differences between the first and second mass ejection events. After the first ejection event occurs, the envelope is inflated temporarily on the Kelvin-Helmholtz timescale. Thus, when the second mass ejection takes place consecutively in the inflated envelope, it shows fainter, redder, and long-term ejection. This result conflicts with observations for SN 2009ip during the outburst phase in 2011 and, therefore the symmetric mass ejection model from a single star must be ruled out for this event. Erupted material from the second ejection collides with the prior CSM from the first ejection and alter the density profile of the prior CSM as described in Sect.3.2. This interaction can affect the light-curve of the subsequent CSM interacting SN. Another suggestion of our work is that only a few factors are difference in extra energy makes larger (by a few orders of magnitude) difference in the amount of erupted mass. In other words, a little difference in the progenitor stellar evolution can be amplified and emerges as a significant difference in the observational features during the pre-CCSN phase and SN itself. From this view point, the difference of the progenitor star evolution between SNe IIn and normal SNe II could be smaller than we think. Higher cadence and deeper transient survey in the future will provide us a larger amount of detailed pre-SN activity data and some objects would show multi-peaked luminosity fluctuations. Interpreting them we require to include the effect of multiple ejections and the corresponding altered density structure discussed here.

References

Bilinski, C., Smith, N., Li, W., et al. 2015, MNRAS, 450, 246
Chevalier, R. A. 1982, ApJ, 258, 790
Chugai, N. N. 1990, Soviet Astronomy Letters, 16, 457
Chugai, N. N. 1992, Soviet Astr., 36, 63
Conti, P. S. 1984, in IAU Symposium, Vol. 105, Observational Tests of the Stellar Evolution Theory, ed. A. Maeder & A. Renzini, 233
Daniels, B. & Soker, N. 2019, MNRAS, 482, 2277

Kuriyama and Shigeyama: The first and second mass ejection
Appendix A: Detailed methods of making the two progenitor models using MESA

The two progenitor models, RSG and BSG, which were used in our simulation as the initial models, were made by using a stellar evolution code MESA release 10398 (Paxton et al. 2011, 2013, 2015, 2018, 2019).

According to Table 1, initial mass and metallicity were set to the following values and we started to make these models evolved.

| Parameter            | Value                  |
|----------------------|------------------------|
| initial_mass         | 15.0d0                 |
| initial_z (RSG)      | 0.02d0                 |
| Zbase (RSG)          | 0.02d0                 |
| initial_z (BSG)      | 0.0002d0               |
| Zbase (BSG)          | 0.0002d0               |

After the termination of main sequence, we set the following options which designate the method of opacity and mass loss.

| Option                          | Value      |
|---------------------------------|------------|
| use_Type2_opacities             | .true.     |
| cool_wind_RGB_scheme            | 'Dutch'    |
| cool_wind_AGB_scheme            | 'Dutch'    |
| RGB_to_AGB_wind_switch          | 1d-4       |
| Dutch_scaling_factor            | 0.8        |

Parameters other than those above were set to default values throughout the entire calculation.

We stopped the calculation 11.2 yr before core-collapse (model RSG) and 7.2 yr before core-collapse (model BSG) and adopted as initial models for our calculations.