

EC-SNe FROM SUPER-ASYMPTOTIC GIANT BRANCH PROGENITORS: THEORETICAL MODELS VERSUS OBSERVATIONS

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ABSTRACT

Using a parametric approach, we determine the configuration of super-asymptotic giant branch (super-AGB) stars at the explosion as a function of the initial mass and metallicity, in order to verify if the electron-capture supernova (EC-SN) scenario involving a super-AGB star is compatible with the observations regarding SN2008ha and SN2008S. The results show that both the supernovae (SNe) can be explained in terms of EC-SNe from super-AGB progenitors having a different configuration at the collapse. The impact of these results on the interpretation of other subluminescent SNe is also discussed.

Key words: stars: AGB and post-AGB – stars: evolution – supernovae: general – supernovae: individual (SN2008ha, SN2008S)

1. INTRODUCTION

It is widely accepted that there are two main explosion mechanisms leading to supernova (SN) events (e.g., Woosley & Weaver 1986; Hillebrandt & Niemeyer 2000): the thermonuclear runaway in white dwarfs (WDs) approaching the Chandrasekhar mass and the core collapse of stars with initial mass $\gtrsim 8 M_{\odot}$ (CC-SNe). From an observational point of view, the former mechanism originates the relatively homogeneous type Ia SNe. The latter produces a huge variety of displays (different energetics and amounts of ejected material, reflecting on heterogeneous light curves and spectra evolutions), which are thought to be linked to the possible interaction of the CC-SN ejecta with circumstellar material (CSM) and the different configuration of the CC-SN progenitor at the time of the explosion (e.g., Filippenko 1997; Hamuy 2003; Turatto 2003; Turatto et al. 2007).

However, the exact nature of CC-SN progenitors (initial mass, stellar structure, and composition at the explosion) and the type of collapse (iron core collapse or neon–oxygen core collapse triggered by electron captures) are far from being well established. There are still ambiguities that arise, on the theoretical side, from the uncertainties in modeling stellar evolution and the explosion mechanism (e.g., Woosley et al. 2002; Heger et al. 2003) and, on the observational side, from the sparse direct detections of progenitor stars and a controversial classification of some events (e.g., Smartt et al. 2009; Turatto et al. 2007).

A number of faint transients have been recently discovered whose nature is still ambiguous and extensively debated. In particular, SN2008S received a SN designation by Stanishev et al. (2008), but Steele et al. (2008) considered it an SN “impostor,” and Smith et al. (2009) considered it the exotic eruption of a luminous blue variable (LBV) object with a relatively low-mass, highly obscured progenitor ($\lesssim 15 M_{\odot}$). An eruptive origin was invoked also for two other similar transients (M 85 OT2006-1 and NGC 300 OT2008-1; Kulkarni et al. 2007; Berger et al. 2009; Bond et al. 2009). However, work based on multiwavelength follow-up of the transients and mid-IR images analysis of the pre-explosion environments not only failed to rule out an SN origin (Pastorello et al. 2007; Prieto et al.

2008) but also suggested that they may be CC-SNe triggered by electron-capture reactions (the so-called EC-SNe) involving a super-asymptotic giant branch (super-AGB) star (Thompson et al. 2008). The long-term multiwavelength monitoring of SN2008S and new comparisons with the two aforementioned transients seem to support the EC-SN interpretation (Botticella et al. 2009, B09 hereafter). In particular, B09 favor a scenario where the SN2008S progenitor is a super-AGB star embedded in an optically thick circumstellar shell. This conclusion is based on (1) the fact that the pre-explosion luminosity of the progenitor is in plausible agreement with the super-AGB models, (2) the capability of super-AGB stars to form thick circumstellar shells through mass loss during the thermal pulses phase, (3) the similarity in the total radiated energy of SN2008S with that of other faint SNe, (4) the moderate velocities ($\sim 3000 \text{ km s}^{-1}$) of the ejecta, and (5) a low but significant mass ($0.0014 \pm 0.0003 M_{\odot}$) of ejected ^{56}Ni .

An EC-SN explanation has been suggested also for SN2008ha (Valenti et al. 2009, V09 hereafter), although an iron CC-SN involving a massive star (initial mass $\gtrsim 25\text{--}30 M_{\odot}$) plus fallback onto the collapsed remnant cannot be ruled out. At first, this object was included among the SN2002cx-like variety of peculiar type Ia SNe (Li et al. 2003; Jha et al. 2006; Phillips et al. 2007), but V09 reviewed the thermonuclear scenario on the basis of the photometric and spectroscopic similarity to low-luminosity CC-SNe, concluding that all SN2002cx-like objects could be indeed faint, stripped-envelope CC-SNe and that SN2008ha represents the faint tail in the luminosity distribution of this SN family. However, Foley et al. (2009) did not definitively rule out the thermonuclear origin of the SN2002cx-like objects, and proposed to explain the peculiarity of SN2008ha in terms of an “accretion-induced” collapse (the so-called AIC mechanism; see Metzger et al. 2009, for details).

So far no clear picture has emerged and different scenarios may explain the aforementioned faint transients, especially because a detailed scrutiny of the super-AGB progenitors configuration at the explosion, which is crucial for a comparison with SN observables, is still missing. In the light of the most recent super-AGB stars models (e.g., Siess & Pumo 2006, SP06

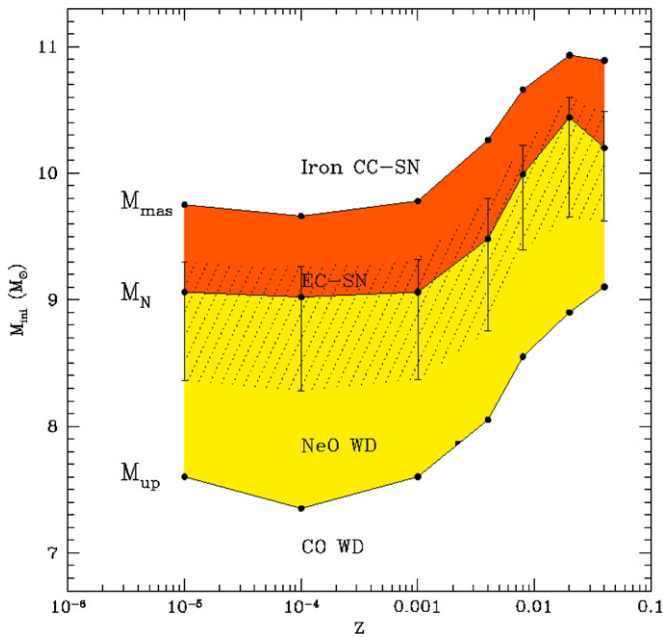


Figure 1. Mass transitions M_{up} , M_N , and M_{mas} as a function of the initial metallicity Z . The error bars indicate the possible range of variation of M_N (the dashed area is used to mark the range of uncertainty) caused by indeterminations on the mass loss and core growth rates. The different outcomes of stellar evolution are also reported: CO WD for stars having initial mass less than M_{up} , NeO WD for stars having initial mass between M_{up} and M_N (see the yellow zone), EC-SN for stars having initial mass between M_N and M_{mas} (see the orange zone), and iron CC-SN for stars having initial mass greater than M_{mas} (figure adapted from Pumo 2007; details on the data can be found in P06 and S07).

hereafter; Pumo 2006, P06 hereafter; Siess 2007, S07 hereafter; Poelarends et al. 2008), in this Letter we discuss in detail the possible link between EC-SNe from super-AGB progenitors and these transients using a parametric approach. After a brief sketch of the super-AGB stars’s evolution, we determine their configuration at the explosion as a function of the initial mass and metallicity from the most recent grids of super-AGB stellar models, and then we investigate if such a configuration is compatible with the observations.

2. EVOLUTION AND FINAL FATE OF SUPER-AGB STARS

Current views on stellar evolution reveal the existence of two critical initial masses: M_{up} , defined as the minimum initial mass above which C-burning ignites, and M_{mas} , corresponding to the minimum initial mass for the completion of all the nuclear burning phases leading to an iron core collapse (e.g., Woosley et al. 2002). The so-called super-AGB stars fill the gap between M_{up} and M_{mas} . After the central He-burning, these stars develop partially degenerate CO cores that are massive enough to exceed the threshold value for C-burning ignition that transforms the core into a degenerate NeO mixture (e.g., P06; S07). The gravothermal energy released by the core contraction after the central He-exhaustion induces the occurrence of the second dredge-up or dredge-out phenomenon (e.g., Ritossa et al. 1999), which increases the He abundance in the envelope up to $Y \sim 0.38$ (see, e.g., Figure 1 in Pumo et al. 2008, but also SP06 and S07).

When C-burning stops in the core, the physical conditions are not suitable for the Ne-ignition and the structure of super-AGB stars becomes very similar to that of AGB stars, having an inert core surrounded by a He- and H-burning shell. Thus, super-AGBs can be considered high-mass equivalent to AGBs and,

as such, they may suffer thermal pulses and lose mass as “normal” (but quite massive and luminous) AGB stars (e.g., Pumo et al. 2008, and references therein). In this situation, the H-free core grows in mass and, if it reaches the Chandrasekhar limit ($M_{\text{CH}} \sim 1.37 M_{\odot}$; Nomoto 1984), EC reactions are activated first on ^{24}Mg and ^{24}Na and then on ^{20}Ne and ^{20}F . Since these reactions have the effect to release entropy and decrease the electron mole number Y_e , O-ignition and core collapse are induced almost simultaneously, and a deflagration front (incinerating the material into a nuclear statistical equilibrium composition) forms when the central density reaches $2.5 \times 10^{10} \text{ g cm}^{-3}$ (e.g., Hillebrandt et al. 1984). However, the O-deflagration is too “weak” to avoid the core collapse, so it proceeds up to neutron star density (see Miyaji et al. 1980; Nomoto 1984, for details). This mechanism, leaving a neutron star as remnant, presents distinctive features (e.g., Kitaura et al. 2006; Wanajo et al. 2009): low explosion energy ($\sim 10^{50}$ erg), large Ni/Fe ratio ($\simeq 1-2$), and ejection of small amount of ^{56}Ni (between ~ 0.002 and $\sim 0.004 M_{\odot}$).

Whether or not the stellar core reaches the threshold value M_{CH} for triggering the EC-SN, depends on the interplay between mass loss and core growth (e.g., Woosley et al. 2002; Herwig 2005). If mass loss is high enough, the envelope is lost before the core can reach M_{CH} , and the endpoint of super-AGB evolution is a NeO WD. In contrast, if the mass loss is not so efficient, the super-AGB star evolves into an EC-SN. The critical initial mass setting the transition between super-AGBs that evolve into a NeO WD and the ones that undergo EC-SN is referred to as M_N .

Recent studies (SP06; P06; S07; Poelarends et al. 2008) have shown that EC-SN channel may exist, but uncertainties in mass loss and core growth rates hamper any conclusions on the exact fraction of super-AGBs evolving into this channel (see Figure 1). So the actual realization of the EC-SN mechanism in super-AGBs should be taken with caution. Nevertheless, it is fair to consider this scenario and its implications.

3. OUTCOME OF EC-SNe FROM SUPER-AGB PROGENITORS

As already mentioned in Section 1, for the comparison with SN observations it is crucial to know the configurations of the progenitors at the explosion. In fact, as explained below, the least massive super-AGB progenitors (i.e., super-AGBs with initial mass close to M_N) may have lost almost all their envelopes at the time of the explosion, while the most massive ones (i.e., super-AGBs with initial mass close to M_{mas}) may still retain massive ($\sim 8-9 M_{\odot}$) envelopes. Also the circumstellar material (CSM) can be different with dense shells in proximity of the most massive super-AGBs progenitors and much looser CSM in proximity of the lower-mass progenitors.

These diversities imply that EC-SNe may be observed as relatively faint type II SNe (IIP or IIL depending on the mass of the H-rich envelope) with presumably low degree of CSM interaction, as type IIb SNe having stronger interaction with dense, structured, and possibly He-enhanced (thanks to the second dredge-up or dredge-out) CSM, up to stripped-envelope SNe.

In Table 1, we summarize the main parameters describing the structure of super-AGB stars of different initial mass and metallicity at the time of explosion. These were built starting with the calculation of the stellar structure at the beginning of the thermally pulsing super-AGB (TP-SAGB) phase from the grids of fully super-AGB stellar models reported in P06 and

Table 1
Features of the Super-AGB Models

M_{\star}^{ini} (M_{\odot})	$M_{\star}^{\text{postCB}}$ (M_{\odot})	$M_{\text{core}}^{\text{postCB}}$ (M_{\odot})	Δt_{CH} (10^5 yr)	M_{ej} (M_{\odot})	$D_{\text{CSM}}^{\text{max}}$ (10^5 AU)
$Z = 0.004$					
9.48	9.36	1.24	3.02	~0.01	6.4
9.55	9.43	1.26	2.24	0.3	6.0
9.75	9.63	1.27	2.04	1.1	4.3
9.95	9.84	1.31	1.25	4.1	2.6
10.15	10.04	1.35	0.46	7.0	1.0
10.25	10.14	1.37	0.07	8.5	0.1
$Z = 0.008$					
9.99	9.77	1.25	2.39	~0.01	5.0
10.01	9.82	1.26	2.23	0.3	4.7
10.15	9.97	1.28	1.77	2.4	3.7
10.35	10.17	1.31	1.11	4.9	2.4
10.55	10.38	1.35	0.46	7.4	1.0
10.65	10.49	1.36	0.10	8.8	0.2
$Z = 0.02$					
10.44	10.15	1.24	2.52	~0.01	5.3
10.46	10.16	1.25	2.47	0.2	5.2
10.55	10.25	1.27	2.02	1.8	4.3
10.65	10.35	1.29	1.52	3.7	3.2
10.75	10.45	1.32	1.01	5.5	2.1
10.85	10.55	1.34	0.51	7.4	1.1
10.92	10.63	1.36	0.10	8.9	0.2

Notes. Selected features (see the text in Section 3) of the super-AGB models as a function of the initial stellar mass for different Z values. The first and the last row in each set of models with a given Z refers to a super-AGB star with initial mass equal to M_N and M_{mas} (to less than $0.01 M_{\odot}$), respectively.

S07. Afterward, the structure at the explosion was calculated, considering that the envelope mass at the explosion may be estimated as follows:

$$M_{\text{env}}^{\text{EC-SN}} = M_{\star}^{\text{postCB}} - M_{\text{CH}} - \Delta M_{\text{loss}}^{\text{postCB}}, \quad (1)$$

where $M_{\star}^{\text{postCB}}$ is the total stellar mass at the beginning of the TP-SAGB phase and $\Delta M_{\text{loss}}^{\text{postCB}}$ is the mass lost during the TP-SAGB evolution. This last term can be estimated from the relation

$$\Delta M_{\text{loss}}^{\text{postCB}} = \overline{M}_{\text{loss}} \cdot \Delta t_{\text{CH}}, \quad (2)$$

where $\overline{M}_{\text{loss}}$ is the averaged mass-loss rate during the TP-SAGB evolution and Δt_{CH} is the time interval from the beginning of the TP-SAGB phase until core mass reaches M_{CH} , given by

$$\Delta t_{\text{CH}} = \frac{M_{\text{CH}} - M_{\text{core}}^{\text{postCB}}}{\overline{M}_{\text{core}}}. \quad (3)$$

In this expression, $M_{\text{core}}^{\text{postCB}}$ is equal to the H-free core mass at the beginning of the TP-SAGB phase and $\overline{M}_{\text{core}}$ is equal to the averaged core growth rate during the TP-SAGB evolution.

The values reported in Table 1 are calculated considering a typical core growth rate of $\overline{M}_{\text{core}} = 5 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ (e.g., Poelarends et al. 2006, 2008) and choosing a reasonable value of $\zeta \equiv \frac{\overline{M}_{\text{loss}}}{M_{\text{core}}} = 70$ during the TP-SAGB evolution (“realistic” values for this ratio vary from ~35 to ~100; see S07, for details). This choice for the ζ value corresponds to $\overline{M}_{\text{loss}} = 3.5 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ and is consistent with the value deduced from the

observations (Prieto et al. 2008 estimated a mass-loss rate $\gtrsim 10^{-5} M_{\odot} \text{ yr}^{-1}$ for the progenitor of SN2008S).

In the two last columns of Table 1, we report the total ejected mass evaluated assuming a mass cut of $\sim 1.36 M_{\odot}$ (e.g., Kitaura et al. 2006), and the maximum distance traveled by the CSM lost during the TP-SAGB evolution, calculated assuming an average wind velocity of 10 km s^{-1} .

Although this parametric approach to determinate the structure of super-AGB stars is simplistic, it is completely consistent with the approach used to determine the fraction of super-AGB stars evolving into EC-SNe by P06 and S07, whose models are the basis for our calculation. In addition, it should be noted that more sophisticated synthetic models for super-AGB stars cannot presently reach a much higher precision because no stellar models describing the TP-SAGB evolutionary phase are available at the moment.

4. DISCUSSION AND CONCLUSIONS

The two events SN2008ha and SN2008S find a reasonable interpretation in the aforementioned scenario, and the progenitor mass to be associated with these SNe can be determined, considering the best “global” matching between the features of the super-AGBs models and the observed properties.

Assuming an initial metallicity Z for the progenitors from ~ 0.008 to ~ 0.02 (see, e.g., V09; B09; Foley et al. 2009, for details on the metallicity determination), one obtains that a super-AGB star with initial mass slightly above M_N has $M_{\text{core}}^{\text{postCB}} \lesssim 1.25\text{--}1.26 M_{\odot}$ (see the second row in the set of models in Table 1), while a super-AGB star with initial mass $\sim (M_N + 0.5) M_{\odot}$ has $M_{\text{core}}^{\text{postCB}} \sim 1.34\text{--}1.35 M_{\odot}$ (see the row before the last in the set of models in Table 1). As a consequence, the time Δt_{CH} necessary to the H-free core to reach M_{CH} is $\gtrsim 2.2\text{--}2.5 \times 10^5 \text{ yr}$ in the former case and $\sim 5 \times 10^4 \text{ yr}$ in the latter one. This difference in the time elapsing between the beginning of TP-SAGB phase and the EC-SN event in the two cases, reflects on the configuration at the collapse. The super-AGB star with initial mass slightly above M_N has time to expel almost all the envelope and, consequently, gives rise to a faint stripped-envelope SN characterized by a non-H-rich⁵ ejecta of $\lesssim 0.2\text{--}0.3 M_{\odot}$ with no signatures of prompt CSM interaction, in agreement with the observations of SN2008ha (M_{ej} in the range $0.1\text{--}0.5 M_{\odot}$, e.g., V09; Foley et al. 2009). Assuming an average wind velocity of 10 km s^{-1} , 90% of the total expelled mass can be at a radial distance $\gtrsim 5 \times 10^4 \text{ AU}$ when the EC-SN event takes place. The mean density of the CSM is expected to be $\lesssim 5 \text{ cm}^{-3}$ (this value is likely to be even lower due to a decreased mass-loss rate near the end of the TP-SAGB phase when the mass of the envelope is significantly reduced) that could be sufficiently low not to give rise to significant interaction. The relatively low X-ray emission ($L_X < 5 \times 10^{39} \text{ erg s}^{-1}$; Foley et al. 2009) seems to support this idea, because the CSM can be an efficient X-ray radiator for much higher density ($\sim 10^5\text{--}10^7 \text{ cm}^{-3}$; Chevalier & Fransson 2001).

⁵ We do not have accurate quantitative information about the chemical composition of the ejecta (except for the ^{56}Ni) to be compared to observations of SN2008ha, due to uncertainties of both observational and theoretical nature. However, we speculate that the composition could be non-H-rich. In fact, for this model the ejecta is composed by the H-free stellar layer between the mass cut and M_{CH} (representing $\sim 5\%\text{--}15\%$ by mass of all the ejected mass) and by the remaining envelope mass at the explosion, whose “initial” H-rich composition can be deeply altered by the second dredge-up phenomenon, the so-called Hot Bottom Burning, and the third dredge-up episodes.

In contrast, the super-AGB star with initial mass $\sim(M_N+0.5)M_\odot$ loses $\sim 1.6\text{--}1.8M_\odot$ in $\sim 5 \times 10^4$ yr—consistently with the inferred duration of the so-called dust-enshrouded phase for SN2008S (upper limit equal to $\sim 6 \times 10^4$ yr; Thompson et al. 2008)—and, besides maintaining a massive ($\sim 7.4M_\odot$) envelope at the collapse, could be embedded within a thicker circumstellar envelope (mean density $\sim 90\text{ cm}^{-3}$). Observations of SN2008S (B09) indicate the formation of a detached shell with an inner radius of ~ 90 AU and outer radius of ~ 450 AU having $\sim 0.08M_\odot$ of gas (J. van Loon 2009, private communication). We could reproduce such a shell increasing the mass-loss rate by ~ 15 times above the average value for a relatively short period of ~ 150 yr as a consequence of a He-shell flash episode (see Mattsson et al. 2007, for details). In addition, we find that $\sim 95\%$ of the total expelled mass in the CSM is beyond the aforementioned detached shell, and these findings are in agreement with the presence of dust at a radial distance greater than $\sim 2 \times 10^3$ AU, as inferred from the MIR emission of SN2008S (B09).

Thus, the current understanding of super-AGB stellar evolution is quantitatively consistent with the available data on these two recent faint transients that may be explained in terms of EC-SNe from super-AGB progenitors having a different configuration at the collapse, without resorting to “exotic” scenarios that are not free from uncertainties. As for the “special” eruption of LBV of relatively low mass proposed to explain the features of the SN2008S (Smith et al. 2009), in addition to the problems for reconciling the ejecta velocity $\lesssim 3000\text{ km s}^{-1}$ with a stellar eruption (B09), it is difficult to explain the fact that the slope of the late-time light curve of SN2008S (but also that of the similar event NGC 300 OT; Bond et al. 2009) is surprisingly similar to that expected in a SN explosion when the main mechanism powering the SN luminosity is the radioactive decay of ^{56}Co into ^{56}Fe . As for the AIC mechanism invoked for the SN2008ha, the main problem concerns the high velocity ($\sim 0.1\text{--}0.2c$) not observed in the ejecta and the impossibility to synthesize the observed intermediate-mass nuclei that are predicted by the “standard” (involving a single degenerate binary system) AIC model. The so-called “enshrouded” AIC model involving the merging of two WDs in a binary system (Metzger et al. 2009) might be somewhat less problematic. However, the ejecta velocity, the amount of ^{56}Ni , and the production of intermediate-mass elements are still quantitatively poorly defined, and the role of the possible interaction between the disk wind and the outgoing SN shock has to be explored.

The weakness of the explosion and small amount of ^{56}Ni synthesized make EC-SNe an obvious explanation for low-luminosity core-collapse events with unusual properties that are related to the pre-explosion mass-loss episodes of their super-AGB progenitors and/or to the possible ensuing ejecta/CSM interaction. However, it has been suggested that the EC channel may also account for the properties of some relatively “normal” type II SNe (e.g., Chugai & Utrobin 2000; Kitaura et al. 2006), characterized by low luminosity, small amount of ejected ^{56}Ni , extended plateaus (implying envelope mass of several M_\odot) and slow expansion velocities (e.g., Pastorello et al. 2009). To date, only for two objects of this class (SN2005cs and SN2008bk; Maund et al. 2005; Li et al. 2006; Mattila et al. 2008) clear evidence has been found for low-mass progenitors on pre-explosion images, but the fact that they are super-AGBs is strongly questioned (e.g., Eldridge, Mattila & Smartt 2007). Thus, it remains to be seen what fraction (if any) of low-luminosity type II SNe are EC-SNe and what other, instead,

are more usual iron CC-SNe that experience less energetic than normal explosions (as, for example, if some of them are sufficiently massive to undergo fallback onto the collapsed remnant; see, e.g., Zampieri et al. 2003).

The wide variety of displays expected for EC-SNe may be of interest also in understanding the two unusual events, SN2005E and SN2005cz (Kawabata et al. 2009; Perets et al. 2009). Indeed, this scenario can account for many of the observed characteristic of both SNe (namely, low explosion energy, very low ejected mass, and ejection of small amount of ^{56}Ni), but the possibility to reproduce all the observed properties (as the spectroscopic features and, in particular, the alleged Ca-richness) deserves further investigation.

We are aware that large uncertainties of both theoretical and observational nature are still present on the EC-SN mechanism in super-AGB stars. Nevertheless, we believe that the scenario herein proposed is promising for understanding an increasing number of underenergetic and unusual SNe. Only a combined effort will solve the issue. On one side, we need more accurate observational constraints about the production of intermediate-mass nuclei (specifically C, O, and all the α -elements in general) in low-luminosity SN events. On the other side, more refined future studies on the super-AGB stellar evolution fully describing the TP-SAGB phase, and three-dimensional simulations for examining in detail the nucleosynthesis processes in EC-SNe are desirable.

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