SUPERNova EXPLOsions of SUPER-ASYMPTOTIC GIANT BRANCH STARS: MULTICOLOR LIGHT CURVES OF ELECTRON-CAPTURE SUPERNovAE

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ABSTRACT

An electron-capture supernova (ECSN) is a core-collapse supernova (CCSN) explosion of a super-asymptotic giant branch (SAGB) star with a main-sequence mass $M_{\text{MS}} \gtrsim 8 M_\odot$. The explosion takes place in accordance with core bounce and subsequent neutrino heating and is a unique example successfully produced by first-principle simulations. This allows us to derive a first self-consistent multicolor light curve of a CCSN. Adopting the explosion properties derived by the first-principle simulation, i.e., the low explosion energy of $1.5 \times 10^{50} \text{erg}$ and the small $^{56}\text{Ni}$ mass of $2.5 \times 10^{-3} M_\odot$, we perform a multi-group radiation hydrodynamics calculation of ECSNe and present multicolor light curves of ECSNe of SAGB stars with various envelope masses and hydrogen abundances. We demonstrate that a shock breakout has a peak luminosity of $L \sim 2 \times 10^{44} \text{erg s}^{-1}$ and can evaporate circumstellar dust up to $R \sim 10^{17} \text{cm}$ for the case of carbon dust, that the plateau luminosity and plateau duration of ECSNe are $L \sim 10^{42} \text{erg s}^{-1}$ and $t \sim 60–100 \text{days}$, respectively, and that a plateau is followed by a tail with a luminosity drop by $\sim 4 \text{mag}$. The ECSN shows a bright and short plateau that is as bright as typical Type II plateau supernovae, and a faint tail that might be influenced by the spin-down luminosity of a newborn pulsar. Furthermore, the theoretical models are compared with ECSN candidates: SN 1054 and SN 2008S. We find that SN 1054 shares the characteristics of the ECSNe. For SN 2008S, we find that its faint plateau requires an ECSN model with a significantly low explosion energy of $E \sim 10^{48} \text{erg}$.

Key words: radiative transfer – shock waves – stars: evolution – supernovae: general – supernovae: individual (Crab Nebula, SN 2008S)

Online-only material: color figures

1. INTRODUCTION

A massive star with a main-sequence mass $M_{\text{MS}} \gtrsim 8 M_\odot$ ends up as a core-collapse supernova (CCSN). Core collapse is initiated by electron capture for a star with an O+Ne+Mg core ($M_{\text{MS}} \lesssim 10 M_\odot$) or Fe photodisintegration for a star with an Fe core ($M_{\text{MS}} \gtrsim 10 M_\odot$).

An explosion mechanism of CCSNe is still under investigation, in particular, for the CCSN of a star with an Fe core (Fe CCSN). Recently, sophisticated multi-dimensional simulations discovered that neutrino-driven convection and/or standing-accretion shock instability enhances neutrino heating and initiates an outward flow (see e.g., Janka et al. 2012; Kotake et al. 2012; Burrows 2013; Bruenn et al. 2013 for recent reviews). However, explosion energies $E$ are about one order of magnitude smaller than a canonical value of a normal CCSN ($E \sim 10^{51} \text{erg}$; e.g., SN 1987A, Blinnikov et al. 2000).

The fate of the less-massive star with the O+Ne+Mg core is different from that of the star with an Fe core (Miyaji et al. 1980; Nomoto et al. 1982; Nomoto 1984, 1987; Miyaji & Nomoto 1987). The O+Ne+Mg core is supported by electron degenerate pressure. The mass and density of the O+Ne+Mg core increase through phases of shell burning of He and H. As the O+Ne+Mg core grows, an envelope undergoes mass loss to reduce the H mass and He dredge-up to enhance He abundance. Eventually, the star becomes a super-asymptotic giant branch (SAGB) star (e.g., Siess 2007). When the central density exceeds a critical value ($4 \times 10^{12} \text{kg m}^{-3}$), electrons begin to be captured by magnesium, the degenerate pressure decreases, and thus the O+Ne+Mg core collapses gravitationally (Miyaji et al. 1980; Nomoto et al. 1982).

The ensuing core bounce and neutrino heating can eject the envelope and part of the O+Ne+Mg core because of weak inward momentum carried by the low-density SAGB envelope (Kitaura et al. 2006; Burrows et al. 2007; Janka et al. 2008). The explosion is called an electron-capture supernova (ECSN; Nomoto 1984, 1987). In contrast to the Fe CCSN, the explosion of the ECSN is realized by first-principle simulations (Kitaura et al. 2006; Burrows et al. 2007; Janka et al. 2008) and a two-dimension simulation demonstrates that the explosion takes place almost spherically (Janka et al. 2008). This is the only example of the CCSN being self-consistently produced. However, a low explosion energy derived from the simulation ($E \sim 10^{50} \text{erg}$) discriminates the ECSN from the normal CCSNe.

The first-principle hydrodynamics simulation enables self-consistent studies, e.g., on nucleosynthesis and observational features. Explosive nucleosynthesis in the ECSN is calculated by Hoffman et al. (2008) and Wanajo et al. (2009) based on Kitaura et al. (2006). They find a small amount of $^{56}\text{Ni}$ in the ejecta [$M(^{56}\text{Ni}) \sim 0.003 M_\odot$] and large production of elements with $Z = 30–40$. The small $^{56}\text{Ni}$ mass is also decidedly different from the normal CCSNe with $M(^{56}\text{Ni}) \sim 0.07 M_\odot$. However, a theoretical light curve of the ECSN has not been presented and the observational features of the ECSN are not yet theoretically clarified.

There are several SNe which are suggested to be ECSNe. One of the old examples is the Crab Nebula being a remnant of SN 1054. This is suggested from high He abundance
envelopes with binding energies of $M_{\text{env}}(\text{cyan})$, and abundance are influenced by (MacAlpine & Satterfield 2008), small ejecta mass (Fesen et al. 1995). One of the recent examples is SN 2008S (Prieto et al. 2008; Botticella et al. 2009), which is suggested from a dust-surrounding bright progenitor and its faintness and slow evolution. Other SN 2008S-like objects have also been discovered (e.g., Bond et al. 2009; Szczygielet et al. 2012).

In this Letter, we adopt the explosion properties derived by state-of-the-art first-principle simulations and present the first self-consistent multicolor light curves of ECSNe. We also investigate the contribution from a continuous energy release from a central remnant as the Crab pulsar. Finally, we compare the multicolor light curves with observations of ECSN candidates.

2. MODEL

We take an O+Ne+Mg core model with $1.377 M_\odot$ at a presupernova stage from Nomoto et al. (1982) and Nomoto (1984, 1987). The model is a core of a star with $M_{\text{MS}} = 8.8 M_\odot$ which is calculated from an He star with $2.2 M_\odot$. A mass range of stars with the O+Ne+Mg core is $M_{\text{MS}} \sim 7–9.5 M_\odot$, but a progenitor of the ECSN should possess an SAGB envelope (see Langer 2012 for a review), of which mass and abundance are influenced by $M_{\text{MS}}$, mass loss, and third dredge-up associated with thermal pulses. However, the mass loss is highly uncertain and no calculation of the full thermal pulses has been available. For almost fully convective envelope models of the progenitor, therefore, we adopt various envelope masses $M_{\text{env}} = (2.0–4.7 M_\odot)$ and hydrogen abundances $X_{\text{env}}(\text{H}) = (0.2–0.7)$ by constructing hydrostatic and thermal equilibrium envelopes with binding energies of $< 10^{48}$ erg (e.g., Saio et al. 1988). Density structures are shown in Figure 1. The luminosity of the progenitor models is $L \sim 3 \times 10^{38}$ erg s$^{-1}$ (Nomoto 1987) and their radii are $R \sim 7 \times 10^9$ km. Figure 2 demonstrates that the luminosity is roughly consistent with the progenitor of SN 2008S (Prieto et al. 2008; Botticella et al. 2009) and is located at a bright tip of the SAGB stars (Siess 2007).

The explosion is initiated by a thermal bomb$^5$ with the explosion energy derived by the first-principle simulation ($E = 1.5 \times 10^{50}$ erg; e.g., Kitaura et al. 2006). The subsequent evolution is followed by a multi-group radiation hydrodynamical code STELLA (Blinnikov et al. 1998, 2000, 2006), in which one-group $\gamma$-ray transfer is calculated and in situ absorption of positron is assumed for energy deposition from $^{56}\text{Ni}–^{56}\text{Co}$ radioactive decay. An abundance distribution in the O+Ne+Mg core after the explosion and the mass of heavy elements are taken from the Model ST in Wanajo et al. (2009), which yields $2.5 \times 10^{-3} M_\odot$ of $^{56}\text{Ni}$. We note that no $^{56}\text{Ni}$ is synthesized in the envelope due to the low temperature of $< 2 \times 10^9$ K.

We also investigate the contribution from the pulsar spin-down luminosity that could be bright at birth. For example, the initial spin-down luminosity of the Crab pulsar was $3.3 \times 10^{39}$ erg s$^{-1}$. Since the pulsar spin-down luminosity can vary in individual ECSNe and the deposition efficiency of the energy released from the pulsar is unknown, we expediently adopt the initial spin-down luminosity of the Crab pulsar and assume that the released energy is fully deposited at the bottom of the ejecta (“full deposition”) or deposited pursuant to the same one-group transport as $\gamma$-rays from the radioactive decay (“one-group transport”).

3. EVOLUTION OF ELECTRON-CAPTURE SUPERNOVAE

In the explosion of the model with $M_{\text{env}} = 3.0 M_\odot$ and $X_{\text{env}}(\text{H}) = 0.2$ (Figures 3(a) and (b)), a shock wave is accelerated up to $9.6 \times 10^9$ km s$^{-1}$ during the first 0.1 s due to the steep density gradient at the bottom of the envelope and decelerated

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$^5$ This does not affect the result because thermal energy is efficiently converted to kinetic energy by the steep density gradient until a shock emerges from a stellar surface (Section 3).

$^6$ This is estimated from the current spin-down luminosity ($L_{\text{sd}} \sim 5 \times 10^{37}$ erg s$^{-1}$; Hester 2008) with an equation $L_{\text{sd}}(t) = L_{\text{sd}0}(1 + t/t_{\text{sd}})^{n+1}/(n+1)$, where $L_{\text{sd}0}$, $t_{\text{sd}}$ ($= 700$ yr) and $n$ (2.5) are the initial spin-down luminosity, a spin-down timescale, and a braking index of the Crab pulsar, respectively.
down to $1.4 \times 10^3$ km s$^{-1}$ by shock emergence from the stellar surface. Such a drastic deceleration of the shock develops severe Rayleigh–Taylor instability.

At the shock emergence, the ECSN flashes (Figure 4(a)). The phenomenon is called a shock breakout, bolometrically brightest. Hereafter, we set $t = 0$ at the shock breakout. A peak wavelength at the shock breakout is $\sim 200$ Å and the bolometric luminosity is as bright as $L = 2.4 \times 10^{42}$ erg s$^{-1}$. Adopting a dust evaporation radius (Dwek 1983) and evaporation temperature for a short flash (Pearce & Mayes 1986), the shock breakout can destroy the circumstellar dust up to $\sim 9.6 \times 10^{11}$ km for the case of carbon dust.

As the SN ejecta cools down, the ECSN enters a plateau phase lasting $t_{\text{plateau}} \sim 60–100$ days. The plateau luminosity is $L_{\text{plateau}} \sim 10^{42}$ erg s$^{-1}$, which is as bright as typical Type II plateau supernovae (SNe II-P; e.g., SN 2004et, Sahu et al. 2006), and the photospheric velocity at the plateau is $3000–4000$ km s$^{-1}$, which is slightly slower than typical SNe II-P. The plateau luminosity is fainter and the duration is longer for an explosion of a star with a larger $M_{\text{env}}$ and a higher $X_{\text{env}}(\text{H})$. The plateau is followed by a tail. The luminosity suddenly fades by $\sim 4$ mag at the transition because of the small $M(^{56}\text{Ni})$. The tail luminosity declines gradually at a rate of 0.012–0.016 mag day$^{-1}$, which is slightly faster than the energy release rate from the $^{56}\text{Co}$ decay.

The multicolor light curves of the model with $M_{\text{env}} = 3.0 M_\odot$ and $X_{\text{env}}(\text{H}) = 0.2$ are shown in Figure 4(b). The photospheric temperature decreases after the shock breakout. Thus, the peak wavelength shifts to redder bands with time and the optical luminosity increases gradually. The light curves in the bluer bands peak at earlier epochs, e.g., $t \sim 10$ days in the $u$ band and $t \sim 20$ days in the $g$ band. In contrast to typical SNe II-P, the $u$ and $g$ light curves do not show a plateau and begin to decline immediately after the peak. The light curves in the bands redder than the $i$ band peak at the end of the plateau. The multicolor light curves drop at the transition to the tail as the bolometric light curve does. The decline rates of the tail are higher for the bluer bands.

The pulsar spin-down only influences the tail because the spin-down luminosity of the Crab pulsar is much fainter than the plateau luminosity. The ECSN shines with the energy release from the $^{56}\text{Co}$ decay at the beginning of the tail and then the energy release from the newborn pulsar becomes dominant at a late phase ($t \gtrsim 250$ days; Figure 4(c)). The tail luminosity is floored in the full deposition model, while the decline rate is lowered in the one-group transport model. The tail luminosity can be $\sim 2$–6 mag brighter than the model without the pulsar contribution at $t = 600$ days.

4. COMPARISON WITH THE OBSERVATIONS

4.1. Crab Nebula and SN 1054

The Crab Nebula is the most famous and conspicuous supernova remnant. Optical and UV observations illustrate that
the Crab Nebula is notably He-rich (X(He) ~ 0.6–0.9; e.g., MacAlpine & Satterfield 2008). In addition to the He-rich abundance, a small ejecta mass (Mej = 4.6 ± 1.8 M⊙; Fesen et al. 1997) and low kinetic energy (E < 3 × 10^{49} erg; e.g., Frail et al. 1995) suggest that the Crab Nebula is a remnant of the ECSN.

An expansion of the Crab Nebula was discovered in the early 1920s (Duncan 1921) and, in the same year, the proximity of the Crab Nebula to SN 1054 was indicated (Lundmark 1921). An explosion date estimated by turning back the expansion is consistent with SN 1054 (Rudie et al. 2008). Hence, it is widely believed that the expanding Crab Nebula is a remnant of SN 1054.

A sudden appearance of SN 1054 was recorded in medieval times and its optical light curve is enscribed in historiographies (Pskovskii 1985; Stephenson & Green 2002). They described the dates of the first and last sightings and its brightness. However, the medieval observations were rough and unconfident. Thus, the reliability of the archives is deeply scrutinized by Stephenson & Green (2002). Referring to the conclusion of that paper, we adopt the following three points with error bars of 1 mag and 20 days: (1) SN 1054 was as bright as Venus (optical magnitude m_{opt} ~ −3.5 to −5) on July 4, 1054 and may have been visible earlier than July 4, 1054 (e.g., May 10, 1054), (2) SN 1054 was visible in the daytime for 23 days from July 4, 1054 and m_{opt} ~ −3 on July 27, 1054, and (3) SN 1054 disappeared on the night of April 6, 1056 with m_{opt} ~ 6. We correct the distance (D = 2 kpc; Trimble 1973) and reddening (E(B − V) = 0.52; Miller 1973) to the Crab Nebula.

We compare an “optical” light curve of the model with M_{env} = 3.0 M⊙ and X_{env}(H) = 0.2 against the observations of SN 1054 (Figure 5(a)). Here, an optical peak of the model is set to be July 4, 1054. The ECSN model well reproduces the brightness and short plateau of SN 1054. The epoch of the transition from the plateau to the tail corresponds to the date at which SN 1054 disappeared from the daytime sky.

The tail luminosities of the full deposition and one-group transport models are brighter and fainter than SN 1054, respectively. If the deposition efficiency is the middle of these models, then a gradually declining optical light curve can cross with the last observation of SN 1054. We note that the last point of SN 1054 is not compatible with the ECSN model without the pulsar contribution, as suggested in Sollerman et al. (2001).

4.2. SN 2008S

SN 2008S is suggested to be the ECSN because the progenitor is bright and surrounded by dust and because SN 2008S is faint and evolves slowly (Botticella et al. 2009). However, the plateau luminosity of the ECSN is as bright as that of normal SNe II-P due to the large pre-supernova radius (Figure 4(a)). Thus, we conclude that the ECSN model based on the first-principle simulation (Kitaura et al. 2006) is incompatible with the faintness of SN 2008S (Figure 5(b)).

However, there is a caveat that the plateau luminosity and duration depend on E and M_{env} (L_{plateau} \propto E^{5/6} M_{env}^{1/2} and t_{plateau} \propto E^{-1/6} M_{env}^{1/2}; Litvinova & Nadezhin 1985; Popov 1993; Eastman et al. 1994). If an explosion energy may be different for individual ECSNe, e.g., due to rotation, then the faint

\footnote{Here, M_{ej} = 1–2 M⊙ is assumed. The kinetic energy is doubled by adopting M_{ej} = 4.6 ± 1.8 M⊙.}

\footnote{An optical bandpass is assumed to be a normal distribution with a peak at 5550 Å and a root-mean-square deviation of 550 Å (Vos 1978).}

and slowly evolving SN 2008S could be explained. Applying the scaling laws and taking L_{plateau} \sim 1 \times 10^{44} \text{ erg s}^{-1} and t_{plateau} \sim 140 days of SN 2008S, we can derive its explosion properties: E \sim 3.5 \times 10^{58} \text{ erg} and M_{env} \sim 3.4 M⊙. A series of first-principle simulations and light curve calculations are required to confirm that such explosion is feasible and explain the multicolor light curves of SN 2008S.

5. DISCUSSION AND CONCLUSION

We present multicolor light curves of ECSNe with various M_{env} and X_{env}(H) based on the results of the first-principle simulation (Kitaura et al. 2006). We demonstrate that the shock breakout has a peak luminosity of L \sim 2 \times 10^{44} \text{ erg s}^{-1} and can evaporate circumstellar dust up to R \sim 10^{12} \text{ km for the case of carbon dust and that the plateau luminosity and the duration of the ECSNe are L_{plateau} \sim 10^{42} \text{ erg s}^{-1} and t_{plateau} \sim 60–100 days, respectively. The brighter and shorter plateau is realized by the model with smaller M_{env} and lower X_{env}(H). The plateau is followed by the tail with the luminosity drop by \sim 4 \text{ mag.}

The tail luminosity declines by 0.012–0.016 mag day\(^{-1}\) for the model without the pulsar contribution, while, if the pulsar contributes to the light curve, the tail light curve is floored or the decline rate is lowered. The contribution from the pulsar spin-down luminosity as bright as the Crab pulsar is prominent only in the tail.
Furthermore, we compare the theoretical models with the ECSN candidates: SN 1054 and SN 2008S.

The bright and short plateau and low explosion energy of the ECSN model are consistent with SN 1054. The plateau is not reproduced with a low-energy explosion of a red supergiant star with heavy $M_{\text{env}}$. The tail luminosity of SN 1054 could be explained by the spin-down luminosity of the newborn Crab pulsar. The deceleration of the shock wave in the ECSN (Figures 3(a) and (b)) is also favorable to produce filamentary structures observed in the Crab Nebula (e.g., Fesen et al. 1997). Thus, the observed features of SN 1054 are naturally reproduced by the ECSN model. The luminosity of the interaction of the ECSN with a circumstellar medium reaches only $10^{-3}$ of the plateau of SN 1054 for a typical SAGB star with a mass loss rate of $10^{-4} M_{\odot}$ yr$^{-1}$ (Smith 2013). Thus, extremely dense and confined ($r < 10^{15}$ cm) circumstellar matter is required to explain the bright and short plateau of SN 1054 (Smith 2013).

The optical light curve of SN 1054 constrains the initial spin-down luminosity of the Crab pulsar. Radio observations suggest $r_{\text{sd}} \lesssim 30$ yr and $L_{\text{sd}}(0) \sim 1.5 \times 10^{42}$ erg s$^{-1}$ to produce relic relativistic electrons (Atoyan 1999). However, such high $L_{\text{sd}}(0)$ leads to a much brighter optical luminosity than SN 1054 on April 6, 1056. Our result favors $r_{\text{sd}} \sim 700$ yr and $L_{\text{sd}}(0) \sim 3.3 \times 10^{39}$ erg s$^{-1}$. These are also supported by a broad spectral evolution model of the pulsar wind nebula (Tanaka & Takahara 2010).

The typical ejecta velocity of the ECSN model with $M_{\text{env}} = 3.0 M_{\odot}$ and $\chi_{\text{env}}(H) = 0.2$ is $v \sim 2.2 \times 10^3$ km s$^{-1}$, which is consistent with the low expansion velocity of the Crab Nebula (Rudie et al. 2008). On the other hand, the velocity of a wind blown from the progenitor is $29$ km s$^{-1}$. Adopting the duration of the SAGB phase ($10^3$ yr; Nomoto et al. 1982; Siess 2007), the SAGB wind extends only up to $9 \times 10^{12}$ km (=$0.30$ pc), which is similar to the apparent size of the Crab Nebula (e.g., Rudie et al. 2008). The radius is smaller than the typical ejecta location of $6.9 \times 10^{13}$ km (=$2.2$ pc). Therefore, the forward shock should be located in a low-density circumstellar wind blown at the core He-burning phase or in an interstellar medium. This could be a reason why the forward shock of the Crab Nebula has not been found.

On the other hand, the plateau of the ECSN model is much brighter than that of SN 2008S. If the explosion energy of the ECSNe is exactly $1.5 \times 10^{50}$ erg as derived by the first-principle simulation (Kitaura et al. 2006), then the multicolor light curves of the ECSN are inconsistent with those of SN 2008S. However, there could be a caveat that the explosion energy may vary on individual ECSNe. The ECSN explosion with $E \sim 3.5 \times 10^{48}$ erg and $M_{\text{env}} \sim 3.4 M_{\odot}$ might be compatible with SN 2008S.

If SN 2008S is the ECSN with $E \sim 3.5 \times 10^{48}$ erg and $M_{\text{env}} \sim 3.4 M_{\odot}$, then we can speculate on shock breakout luminosity and $M^{(56}\text{Ni})$; according to analytic dependence (Matzner & McKee 1999), the luminosity of the shock breakout is $\sim 1.4 \times 10^{42}$ erg s$^{-1}$. Carbon dust at $\lesssim 9.2 \times 10^{10}$ km is evaporated by the shock breakout. The size of a dust-free cavity is roughly consistent with that estimated from a midinfrared observation of SN 2008S (Botticella et al. 2009; but see also Kochanek 2011). The explosion energy is comparable to a gravitational binding energy of the progenitor at $M \geq 1.3755 M_{\odot}$. Thus, SN 2008S is likely to eject materials above the outer edge of the core and yield $M^{(56}\text{Ni}) \sim 4.4 \times 10^{-4} M_{\odot}$, which is slightly smaller than an estimate from the observed tail of SN 2008S (Botticella et al. 2009). Therefore, we propose that the light curve tail of SN 2008S is powered by a spin-down luminosity of a newborn neutron star as SN 1054. We note a caveat that SN 2008S is a Type IIn SN and thus could be contributed to by interacting with the circumstellar medium.

The number of SNe sharing the characteristics of the ECSN, i.e., a bright and short plateau and faint tail, is small if the SN 2008S-like transients are not the ECSNe. We also note that faint and low-energy SNe II-P, e.g., SN 1997D and SN 1999br (Zampieri et al. 2003), have a slower photospheric velocity at the plateau ($v \sim 1000–2000$ km s$^{-1}$) than the ECSN. The scarcity of the ECSNe might stem from a small range of mass of a star ending up as ECSNe at solar metallicity (see Langer 2012 for a review). Since a significant contribution of ECSNe to the production of $^{44}\text{Ca}$, $^{62}\text{Zn}$, and $^{60}\text{Zr}$ is suggested (Wanajo et al. 2009, 2011, 2013), chemical evolution models taking into account the scarcity is required to study the origin of these isotopes.

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9 The filamentary structures can also be originated by interaction between the ECSN ejecta and a pulsar wind nebula (Hester 2008 for a review). However, the structures exist even in the ejecta unaffected by the pulsar (e.g., Rudie et al. 2008). Future 3D calculations will test how the shock deceleration produces the filamentary structures.
