NUCLEOSYNTHESIS IN TYPE Ia SUPERNOVAE

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Among the major uncertainties involved in the Chandrasekhar mass models for Type Ia supernovae are the companion star of the accreting white dwarf (or the accretion rate that determines the carbon ignition density) and the same speed after ignition. We present nucleosynthesis results from relatively slow deagration (1.5 - 3% of the sound speed) to constrain the rate of accretion from the companion star. Because of electron capture, a significant amount of neutron-rich species such as \(^{54}\)Cr, \(^{50}\)Ti, \(^{56}\)Fe, \(^{62}\)Ni, etc. are synthesized in the central region. To avoid the too large ratios of \(^{54}\)Cr/\(^{56}\)Fe and \(^{50}\)Ti/\(^{56}\)Fe, the central density of the white dwarf at the nuclear runaway must be as low as \(< 2 \times 10^9 \text{ g cm}^{-3}\). Such a low central density can be realized by the accretion as fast as \(M_\dot{} > 1 \times 10^{-7} \text{M}_\odot \text{ yr}^{-1}\). These rapidly accreting white dwarfs might correspond to the super-soft X-ray sources.

1. INTRODUCTION

Supernovae of different types have different progenitors, thus producing different heavy elements on different time scales during the chemical evolution of galaxies. Because the lifetime of their massive progenitors is about \(10^6 \text{ yr}\) being much shorter than the age of galaxies, Type II supernovae (SNe II) and Type Ib/Ic supernovae (SNe Ib/Ic) cause the heavy-element enrichment in the early phase of the galactic evolution.

In contrast, Type Ia supernovae (SNe Ia) produce heavy elements on a much longer time scale in the later phase of the galactic evolution. There are strong observational and theoretical indications that SNe Ia are thermonuclear explosions of accreting white dwarfs (e.g., Nomoto et al. 1994 for a review). However, the exact binary evolution that leads to SNe Ia has not been identified (e.g., Renzini 1996; Branch et al. 1995 for recent reviews). The identification of the progenitor’s evolution is critically important 1) for clarifying whether the nature of SNe Ia at high redshift is the same as nearby SNe Ia, and 2) for understanding the origin of some systematic variations of light curves (i.e., brighter/slower), which is a critical material for the determination of cosmological parameters, \(H_0\) and \(q_0\). In this paper, we provide some important constraints on the progenitor system from the view point of nucleosynthesis, namely, the carbon ignition density which is translated into the accretion rate for the Chandrasekhar mass models.
2. NUCLEOSYNTHESIS IN SLOW DEFLAGRATION

For the Chandrasekhar mass white dwarf model, carbon burning in the central region leads to a thermonuclear runaway. An ame front then propagates at a subsonic speed as a deflagration wave due to heat transport across the front (e.g., Nomoto et al. 1996a for a review). Here the major uncertainty is the ame speed which depends on the development of instabilities of various scales at the ame front. Multi-dimensional hydrodynamical simulations of the ame propagation have been attempted by several groups (Livne 1993; Arnett & Livne 1994; Khokhlov 1995; Niemeyer & Hillebrandt 1995). These simulations have suggested that a carbon deflagration wave propagates at a speed $v_{\text{def}}$ as slow as $1.5 - 3\%$ of the sound speed $v_s$ in the central region of the white dwarf. Though the calculated ame speed is still very preliminary, it is useful to examine the nucleosynthesis consequences of such a slow ame speed.

In the deflagration wave, electron capture enhances neutron excess, which depends on both $v_{\text{def}}$ and the central density of the white dwarf $\rho = 6.10^9 \text{ g cm}^{-3}$. The resultant nucleosynthesis in slow deflagration has some distinctive features compared with the faster deflagration like W 7 (Nomoto et al. 1984; Thielemann et al. 1986), thus providing important constraints on these two parameters. The constraint on the central density is equivalent to a constraint on the accretion rate.

We calculate explosive nucleosynthesis for two cases with $\rho = 1.37$ (C) and 2.12 (W) at the thermonuclear runaway, i.e., at the stage when the timescale of the temperature rise in the center becomes shorter than the dynamical timescale. Here C and W imply that the models are the same as calculated for C 6 and W 7, respectively (Nomoto et al. 1987, 1990).

Figure 1. $Y_e$, the total proton to nucleon ratio, and thus a measure of electron captures on proton and nuclei, as a function of radial mass for different models. Here c015, sd015, and sd030 correspond to CS15, WS15, and WD30 in the text.
For the slow (S) de agration, we adopt $v_{\text{def}} = v_s = 0.015$ (WS15, CS15) and 0.03 (WS30). The central region behind the slower de agration undergoes electron capture for a longer time than in W7, thereby having significantly reduced $Y_e$. In Figure 1, profiles of $Y_e$ for these cases and W7 are shown (Thielemann et al. 1996b). In general it can be recognized that small burning front velocities lead to steep $Y_e$-gradient which attain with increasing velocities. Lower central ignition densities shift the curves up (CS15), but the gradient is the same for the same propagation speed.

Figure 2 shows the abundance distribution of neutron-rich species such as $^{54}$Cr, $^{50}$Ti, $^{58}$Fe, and $^{62}$Ni behind the slow de agration for WS15. The locations of $^{54}$Fe and $^{58}$Ni, overproduced in W7, correspond to $Y_e = 0.47-0.485$. Due to the $Y_e$-gradients which are steeper than for W7, the amount of matter in a given $Y_e$-range is reduced, but also smaller central values are attained, giving rise to more neutron-rich nuclei. $Y_e = 0.46$ 26/56 leads to a large abundance of stable $^{56}$Fe (not from $^{56}$Ni decay). $Y_e = 0.44-0.46$ result also in $^{48}$Ca, $^{50}$Ti, $^{54}$Cr, and $^{58}$Fe. Of these nuclei $^{48}$Ca with Z/A = 0.42 is only produced if $Y_e$ approaches values close to and smaller than 0.44 (Woosley 1996; Meyer et al. 1996). As the de agration wave propagates outwards, the white dwarf gradually expands to undergo less electron capture and thus mostly $^{56}$Ni is synthesized. Eventually, the de agration enters the region of incomplete Siburning and explosive O-Ne-C burning.

The neutron excess is sensitive to the initial central density. For WS15 ($\eta = 2.12$), the masses of $^{54}$Cr and $^{50}$Ti are smaller than those for CS15 ($\eta = 1.37$) by a factor of 5 and 20, respectively, and those for WS30 ($v_{\text{def}} = v_s = 0.03$) by a factor of 2 and 4, respectively.
3. NUCLEOSYNTHESES IN DELAYED DETONATION

If the deagration speed continues to be much slower than in W7, the white dwarf undergoes strong pulsation as first found by Nomoto et al. (1976). In this pulsating deagration model, the white dwarf expands to quench nuclear burning when the total energy of the star is still negative. Then the star contracts to burn more material to make the total energy positive ($5 \times 10^{49}$ erg s$^{-1}$).

The deagration might induce a detonation at low density layers. In the delayed detonation model (Khokhlov 1991a; Woosley & Weaver 1994), the deagration wave is assumed to be transformed into detonation at a certain layer during the first expansion phase. In the pulsating delayed detonation model (Khokhlov 1991b), the transition into detonation is assumed to occur near the maximum compression due to mixing.

We study explosive nucleosynthesis with a large reaction network (Thielemann et al. 1996) for various delayed detonation (DD) models, which has not been discussed in detail before (Nomoto et al. 1996b). We artificially transform the slow deagration W S15 into detonation when the density ahead of the same decreases to 3.0, 2.2, and 1.7 $10^{7}$ g cm$^{-3}$ (WDD3, WDD2, and WDD1, respectively, where 3, 2, and 1 indicate $\gamma$ at the transition). Then the carbon detonation propagates through the layers with $< 10^{8}$ g cm$^{-3}$. The explosion energy of three WDD models is $1.5 \times 10^{51}$ ergs s$^{-1}$ and the mass of $^{56}$Ni is $0.73$ M$_{\odot}$ (WDD3), $0.58$ M$_{\odot}$ (WDD2), and $0.45$ M$_{\odot}$ (WDD1).

Figures 3 shows the abundance distribution against the expansion velocity and $M_\gamma$ after the passage of the slow deagration (W S15) and the delayed detonation. For comparison, the abundance distribution of W70 is shown in Figure 4, where the initial metallicity (i.e., the initial CNO elements which are later transformed into $^{22}$Ne) is assumed to be zero.
Figure 4. The abundance distribution in the delayed detonation model W 70 as a function of interior mass and the expansion velocity.

It is seen that WDD2 and WDD1 produce two Si-S-Ar peaks at low velocity (4000 km s\(^{-1}\)) and high velocities (10,000 - 15,000 km s\(^{-1}\)). The low velocity intermediate mass elements are important to observe at late times to distinguish models. In particular, the minimum velocity of Ca in WDD models is 4000 km s\(^{-1}\), which should be compared with the observed minimum velocities of Ca indicated by the red edge of the Ca II H and K absorption blend (Fisher et al. 1995).

Meikle et al. (1996) have observed a P Cyg-like feature at 1.05/1.08 m in SN 1994D and 1991T. They note that, if this feature is due to He, He in SN 1994D is likely to be formed in -rich freeze-out and mixed out to the high velocity layers (12,000 km s\(^{-1}\)). The maximum velocity of He is 5000 - 6000 km s\(^{-1}\) in WDDs being slower than 9000 km s\(^{-1}\) in W 7, so that more extensive mixing of He would be required for WDDs than W 7. Alternatively, if the feature is due to Mg, the Mg velocity is con ned in 12,500 - 16,000 km s\(^{-1}\) in SN 1994D, which is consistent with W 7 (13,000 - 15,000 km s\(^{-1}\)). For WDDs, on the other hand, the minimum velocities of Mg are 14,500 km s\(^{-1}\) (WDD1), 16,500 km s\(^{-1}\) (WDD2), and 18,000 km s\(^{-1}\) (WDD3), and the latter two models seem to have too high velocities.

4. YIELDS OF TYPE IA SUPERNOVAE

Total isotopic compositions of WDD1 - WDD3 are given in Table 1, and compared with the solar abundances in Figure 5 which are normalized to \(^{56}\)Fe. Table 1 also includes W 7 and W 70 updated with the latest reaction rates along with W 70 (Thielemann et al. 1996b). We note:

1) The synthesized amounts of Fe and thus the ratio between the intermediate mass
Figure 5. The ratios of integrated abundances of the delayed detonation model WDD2 after decay of unstable nuclei, normalized to 56Fe, relative to solar abundances.

elements to Fe, SiCa/Fe, are sensitive to the transition density from degeneration to detonation. Among the WDD models, WDD2 produces almost the same amount of 56Ni as W7 (0.6 M⊙) but more SiCa than W7 by a factor of 2 (Fig. 3), since more oxygen is burned in the outer layers. WDD1 has even larger SiCa/Fe ratio, which is close to the solar ratio. Therefore, the measurement of the SiCa/Fe ratio in SNe Ia remnants (Tycho, SN 1006, etc.) would be useful to distinguish the models.

2) Some neutron-rich species such as 54Cr and 50Ti are overproduced with respect to 56Fe. To see the degree of overproduction, we combine nucleosynthesis products of SNe Ia and SNe II with various ratios and compare with solar abundances of heavy elements and their isotopes.

Nucleosynthesis products of SNe II as a function of stellar masses are taken from the calculations by Nomoto & Hashimoto (1988), Hashimoto et al. (1989, 1996) and Thielemann et al. (1996a) as summarized in Tsujimoto et al. (1995). SNe II yields integrated over m_u = 10 M⊙ to m_u = 50 M⊙ with the Salpeter IMF are given in Table I. The upper mass bound m_u is chosen to give [O/Fe] = +0.4, which is consistent with the observations of low metallicity stars for [Fe/H] < 1.0.

Nucleosynthesis products of SNe Ia are those from WDD2 and W70, and the results are shown in Figures 4-7. For WDD2, the best fit to the solar abundances are obtained for the ratio between SNe Ia and SNe II contributions as r = 0.07 where r is the mass fraction contributed by SNe Ia per unit mass of all heavy elements in the gas as defined in Tsujimoto et al. (1995).

Aided with a reasonable chemical evolution model (Yoshii et al. 1996), the number of SNe Ia ever occurred relative to SNe II is determined to be N_{Ia}/N_{II} = 0:12 in order to reproduce the observed abundances. This is consistent with the fact that the observed estimate of SNe Ia frequency is as low as 10 % of the total supernova occurrence (van den
Figure 6. Solar abundance pattern based on synthesized heavy elements from a composite of Type Ia and Type II supernova explosions with the most probable ratio of $r$. Relative abundances of synthesized heavy elements and their isotopes normalized to the corresponding solar abundances are shown by circles. Here WD 2D2 is adopted for the Type Ia supernova model.

Figure 7. Same as Figure 6 but for W 70 as an SN Ia model.
With this relative frequency, $^{56}\text{Fe}$ from SNe Ia is about 50 % of total $^{56}\text{Fe}$. Then the abundance ratios between neutron-rich species and $^{56}\text{Fe}$ could be reduced by a factor of 2. For W 70, the excess of $^{58}\text{Ni}/^{56}\text{Fe}$ is now within the uncertainties (Fig. 7). For W D D s, on the other hand, $^{54}\text{Cr}$ and $^{50}\text{Ti}$ are overproduced as seen in Figure 3 even when the contribution from SNe II is taken into account.

The above results imply that the central density of the Chandrasekhar mass white dwarf at them onuclear run away must be as low as $< 2 \times 10^9$ g cm $^{-3}$, though the exact constraint depends somewhat on the same speed. Such a low central density can be realized by the accretion as fast as $M > 1 \times 10^{-7}$ M$_{\odot}$ yr$^{-1}$. Such rapidly accreting white dwarfs might correspond to the super-soft X-ray sources.

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Table 1
Nucleosynthesis products of SN II and Ia

| Species | Synthesized mass (M) | Type II | Type Ia |
|---------|---------------------|---------|---------|
|         | 10 50M  | W 70  | W 7    | W DD1  | W DD2  | W DD3  |
| ^12C    | 7.93E-02 | 5.08E-02 | 4.33E-02 | 1.80E-03 | 1.15E-03 | 5.82E-04 |
| ^13C    | 3.88E-09 | 1.56E-09 | 1.40E-06 | 3.52E-08 | 1.04E-08 | 6.90E-09 |
| ^14N    | 1.56E-03 | 3.31E-08 | 1.16E-06 | 3.08E-04 | 2.44E-04 | 7.42E-05 |
| ^15N    | 1.66E-08 | 4.13E-07 | 1.32E-09 | 6.84E-07 | 2.75E-07 | 1.68E-07 |
| ^16O    | 1.80    | 1.33E-01 | 1.43E-01 | 9.96E-02 | 6.93E-02 | 4.69E-02 |
| ^17O    | 9.88E-08 | 3.33E-10 | 3.54E-08 | 3.99E-06 | 4.50E-06 | 1.72E-06 |
| ^18O    | 4.61E-03 | 2.69E-03 | 8.25E-03 | 6.96E-07 | 4.62E-07 | 2.42E-07 |
| ^19F    | 1.16E-09 | 1.37E-10 | 5.67E-10 | 1.68E-09 | 8.90E-10 | 5.48E-10 |
| ^20Ne   | 2.12E-01 | 2.29E-03 | 2.02E-03 | 1.45E-03 | 9.13E-04 | 6.77E-04 |
| ^21Ne   | 1.08E-03 | 2.81E-08 | 8.46E-06 | 4.09E-06 | 1.47E-06 | 2.30E-06 |
| ^22Ne   | 1.83E-02 | 2.15E-08 | 2.49E-03 | 1.34E-05 | 1.96E-06 | 1.39E-06 |
| ^23Na   | 6.51E-03 | 1.41E-05 | 6.32E-05 | 3.20E-05 | 1.30E-05 | 6.53E-06 |
| ^24Mg   | 8.83E-02 | 1.58E-02 | 8.50E-03 | 8.29E-03 | 4.76E-03 | 2.93E-03 |
| ^25Mg   | 1.44E-02 | 1.64E-07 | 4.05E-05 | 4.60E-05 | 2.39E-05 | 1.44E-05 |
| ^26Mg   | 2.01E-02 | 1.87E-07 | 3.18E-05 | 5.52E-05 | 3.57E-05 | 1.09E-05 |
| ^27Al   | 1.46E-02 | 1.13E-04 | 9.86E-04 | 4.65E-04 | 2.74E-04 | 1.73E-04 |
| ^28Si   | 1.05E-01 | 1.38E-01 | 1.50E-01 | 3.48E-01 | 2.71E-01 | 2.04E-01 |
| ^29Si   | 8.99E-03 | 6.03E-05 | 8.61E-04 | 6.05E-04 | 3.87E-04 | 2.49E-04 |
| ^30Si   | 8.05E-03 | 3.09E-05 | 1.74E-03 | 1.07E-03 | 6.35E-04 | 3.94E-04 |
| ^31P    | 1.21E-03 | 8.51E-05 | 4.18E-04 | 2.67E-04 | 1.80E-04 | 1.23E-04 |
| ^32S    | 3.84E-02 | 9.19E-02 | 8.41E-02 | 2.09E-01 | 1.65E-01 | 1.24E-01 |
| ^33S    | 1.78E-04 | 5.83E-05 | 4.50E-04 | 3.48E-04 | 2.49E-04 | 1.74E-04 |
| Species | Type II | Type Ia |
|---------|---------|---------|
|         | 10 M   | 50 M   | W 70 | W 7 | W D D 1 | W D D 2 | W D D 3 |
| $^{34}\text{S}$ | 2.62E-03 | 2.84E-06 | 1.90E-03 | 3.42E-03 | 2.50E-03 | 1.75E-03 |
| $^{36}\text{S}$ | 1.78E-06 | 1.09E-11 | 3.15E-07 | 2.29E-07 | 1.33E-07 | 8.58E-08 |
| $^{35}\text{Cl}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |
| $^{37}\text{Cl}$ | 1.88E-05 | 5.36E-06 | 3.98E-05 | 4.23E-03 | 3.36E-05 | 2.52E-05 |
| $^{36}\text{Ar}$ | 6.62E-03 | 1.99E-02 | 1.49E-03 | 4.12E-02 | 3.35E-02 | 2.05E-02 |
| $^{38}\text{Ar}$ | 1.37E-03 | 5.93E-07 | 1.06E-03 | 1.71E-03 | 1.45E-03 | 1.12E-03 |
| $^{40}\text{Ar}$ | 2.27E-08 | 1.14E-12 | 1.26E-08 | 8.16E-09 | 6.08E-09 | 4.53E-09 |
| $^{39}\text{K}$ | 6.23E-05 | 1.82E-06 | 8.52E-05 | 1.05E-04 | 9.00E-05 | 7.00E-05 |
| $^{41}\text{K}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |
| $^{40}\text{Ca}$ | 5.77E-03 | 1.95E-02 | 1.49E-02 | 4.12E-02 | 3.35E-02 | 2.05E-02 |
| $^{42}\text{Ca}$ | 1.37E-03 | 5.93E-07 | 1.06E-03 | 1.71E-03 | 1.45E-03 | 1.12E-03 |
| $^{43}\text{Ca}$ | 2.27E-08 | 1.14E-12 | 1.26E-08 | 8.16E-09 | 6.08E-09 | 4.53E-09 |
| $^{44}\text{Ca}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |
| $^{45}\text{Sc}$ | 6.23E-05 | 1.82E-06 | 8.52E-05 | 1.05E-04 | 9.00E-05 | 7.00E-05 |
| $^{46}\text{Ti}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |
| $^{47}\text{Ti}$ | 2.27E-08 | 1.14E-12 | 1.26E-08 | 8.16E-09 | 6.08E-09 | 4.53E-09 |
| $^{48}\text{Ti}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |
| $^{49}\text{Ti}$ | 2.27E-08 | 1.14E-12 | 1.26E-08 | 8.16E-09 | 6.08E-09 | 4.53E-09 |
| $^{50}\text{Ti}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |
| $^{51}\text{Ti}$ | 2.27E-08 | 1.14E-12 | 1.26E-08 | 8.16E-09 | 6.08E-09 | 4.53E-09 |
| $^{52}\text{Ti}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |
| $^{53}\text{Ti}$ | 2.27E-08 | 1.14E-12 | 1.26E-08 | 8.16E-09 | 6.08E-09 | 4.53E-09 |
| $^{54}\text{Ti}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |
| $^{55}\text{Mn}$ | 2.27E-08 | 1.14E-12 | 1.26E-08 | 8.16E-09 | 6.08E-09 | 4.53E-09 |
| $^{56}\text{Fe}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |
| $^{57}\text{Fe}$ | 2.27E-08 | 1.14E-12 | 1.26E-08 | 8.16E-09 | 6.08E-09 | 4.53E-09 |
| $^{58}\text{Fe}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |
| $^{59}\text{Co}$ | 2.27E-08 | 1.14E-12 | 1.26E-08 | 8.16E-09 | 6.08E-09 | 4.53E-09 |
| $^{60}\text{Ni}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |
| $^{61}\text{Ni}$ | 2.27E-08 | 1.14E-12 | 1.26E-08 | 8.16E-09 | 6.08E-09 | 4.53E-09 |
| $^{62}\text{Ni}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |
| $^{63}\text{Cu}$ | 2.27E-08 | 1.14E-12 | 1.26E-08 | 8.16E-09 | 6.08E-09 | 4.53E-09 |
| $^{64}\text{Cu}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |
| $^{65}\text{Zn}$ | 2.27E-08 | 1.14E-12 | 1.26E-08 | 8.16E-09 | 6.08E-09 | 4.53E-09 |
| $^{66}\text{Zn}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |
| $^{67}\text{Zn}$ | 2.27E-08 | 1.14E-12 | 1.26E-08 | 8.16E-09 | 6.08E-09 | 4.53E-09 |
| $^{68}\text{Zn}$ | 1.01E-04 | 8.06E-06 | 1.34E-04 | 1.21E-04 | 9.83E-05 | 7.67E-05 |