PRESUPERNOVA EVOLUTION OF 8-12 $M_\odot$ STARS AND THE CRAB NEBULA'S PROGENITOR

Ken'ichi Nomoto
Dept. of Earth Science and Astronomy, College of General
Education, University of Tokyo, Meguro-ku, Tokyo 153
and
Max-Planck-Institut für Physik und Astrophysik
Institut für Astrophysik, Garching bei München

ABSTRACT

The elemental abundances of the Crab Nebula are compared with the presupernova models of 8-12 $M_\odot$ stars. The small carbon abundance of the Crab is consistent with only the star whose main-sequence mass was 8-9.5 $M_\odot$. More massive stars contain too much carbon in the helium layer and smaller mass stars do not leave neutron stars. A scenario for the Crab Nebula's progenitor is proposed.

1. INTRODUCTION

The comparison of the elemental abundances of the young supernova remnant with the nucleosynthesis in the evolving stellar interior gives an important clue to identify the progenitor star of the supernova remnants. Such a comparison has been made mostly between the massive star models ($M \gtrsim 15\ M_\odot$) and the oxygen-rich supernova remnants.

However, little work has been done for 8-12 $M_\odot$ stars although most of Type II supernovae originate from this mass range. In this paper, I summarize the features of the presupernova evolution of 8-12 $M_\odot$ stars based on the recent calculations (Nomoto 1981). In contrast to more massive stars, 8-12 $M_\odot$ stars could eject only a small amount of heavy elements. Thus it is interesting to compare these models with the abundances of the Crab Nebula, because the Crab has been known to contain little heavy elements.

2. PRESUPERNOVA EVOLUTION OF 8-12 $M_\odot$ STARS

The evolution of the helium core of 8-12 $M_\odot$ stars were calculated from the helium burning phase. The mass of the initial helium core (i.e., mass interior to the H-burning shell, $M_{H,0}$), the corresponding main-sequence masses (M), and the mass interior to the He-burning shell (M_{He}), and the C-burning shell (M_C) at the presupernova stages are summarized in Table. In Figures 1-4, shown are the chemical evolution of

J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 139–143.

these stars. (Chemical compositions of these models are seen in Nomoto 1982).

$M/M_\odot$	$M_{H,0}$	M_{He}	M_C	Evolution		
~ 12	3.0	1.62	1.60	.. off-center Si flash	⇒	Fe core collapse (photodisintegration)
~ 10	2.6	1.45	1.43	.. off-center Ne flash		
~ 9.5	2.4	1.375	1.34	no Ne ignition	⇒	O+Ne+Mg core collapse (electron capture)
~ 9	2.2	1.375	1.28			

Since the core masses (M_C in particular) of these stars are close to the Chandrasekhar limit, the effect of electron degeneracy on the evolution is quite significant. Following are the characteristics of the evolution of 8-12 $M_\odot$ stars, which are very sentitive to the stellar mass:

1) Off-Center Flash: When the core (Si core of the 12 $M_\odot$ star and O+Ne+Mg core for $M \lesssim 10$ $M_\odot$) becomes semi-degenerate, the central region is cooled down by the neutrino emission and temperature inversion appears. As a result, Si (for 12 $M_\odot$ star) or Ne (for 10 $M_\odot$ star) ignites off-center as seen in Figures 1 and 2. The Ne burning grows into a very strong flash. However, it is not strong enough to eject the H-He layer, i.e., weaker than the Ne flash of the 10 $M_\odot$ star computed by Woosley et al. (1980) because of our smaller M_C. Although the further evolution is very complicated, the 10 and 12 $M_\odot$ stars finally evolve into the Fe core collapse (Woosley et al. 1980).

2) Formation of Degenerate O+Ne+Mg Core: For stars of $M \lesssim 9.5$ $M_\odot$, the core mass, M_C, is smaller than the critical mass of 1.37 $M_\odot$ for Ne ignition (Boozer et al. 1973). Therefore, the O+Ne+Mg core cools down without Ne burning and becomes strongly degenerate (Figures 3 and 4).

3) Dredging-Up of the He Layer: For the 9.5 $M_\odot$ and 9 $M_\odot$ stars, the core is more centrally condensed than for $M \gtrsim 10$ $M_\odot$ so that the He layer is more extended. When the 9.5 $M_\odot$ reaches the end stage of Figure 3, the He-layer expands greatly and the penetration of the surface convection zone into the He-layer starts. Such a dredging-up of the He-layer starts earlier for the 9 $M_\odot$ star (Figure 4) and proceeds until the hydrogen shell burning is ignited.

3. COLLAPSE OF THE O+Ne+Mg CORE OF 8-10 $M_\odot$ STARS

After the dredging-up of the He layer, both 9 and 9.5 $M_\odot$ stars evolve as follows, which is common to 8-10 $M_\odot$ stars.

1) The H/He double shell burnings form the C+O layer above the O+Ne+Mg core. The temperature of the C+O layer is too low to ignite the carbon shell flash. Then the evolutionary track in the central density, ρ_c, and temperature, T_c, merges into the same track as of the degenerate C+O core of 4-8 $M_\odot$ stars because of the same core growth rate.

2) When M_{He} exceeds 1.375 $M_\odot$, the electron captures on ^{24}Mg and ^{20}Ne

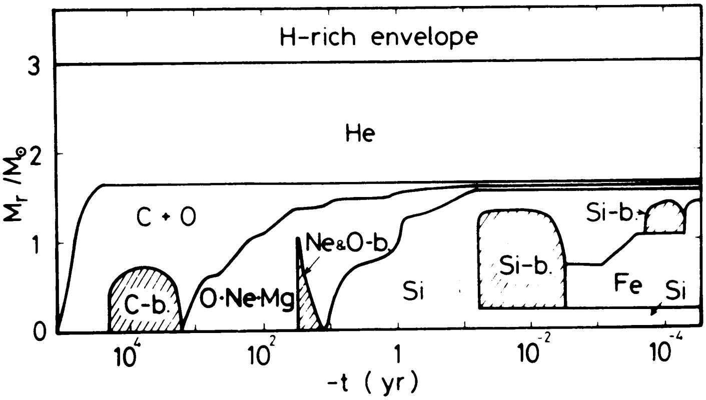

Fig. 1 Chemical Evolution of the 12 $M_\odot$ Star. Time is measured from the ignition of the central Si flash. Shaded regions are in convective equilibrium. (Convective He, C, and Ne burning shells are omitted from the figure.)

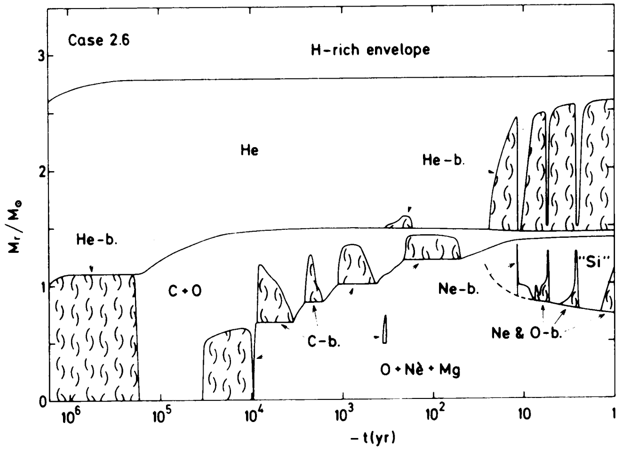

Fig. 2 Chemical Evolution of the 10 $M_\odot$ Star. Time is measured from the end stage of the computation. Curled regions are the convection regions. Off-center Ne flash is ignited.

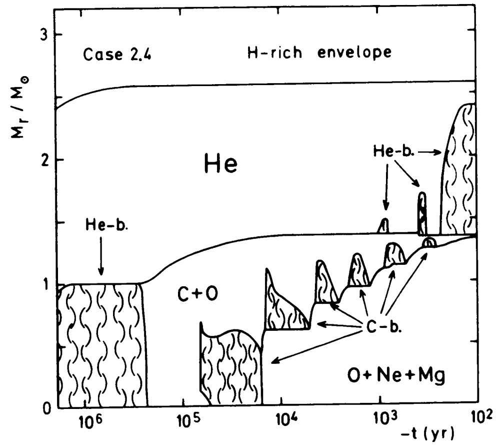

Fig. 3

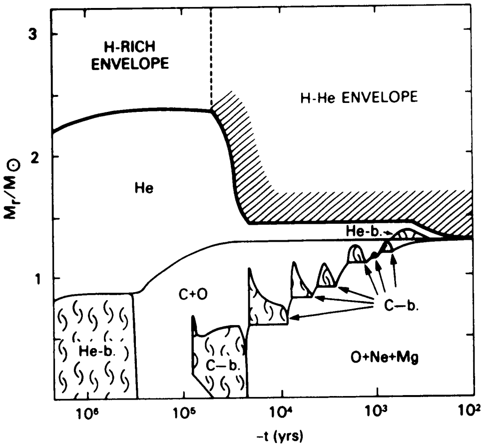

Fig. 4

Same as Fig. 2 but for the 9.5 $M_\odot$ star (Fig. 3) and 9 $M_\odot$ star (Fig. 4) where the degenerate O+Ne+Mg core is formed. Shaded region indicates the surface convection zone penetrating into the He-layer.

start to reduce the number of electrons per baryon, Y_e. Then the core contracts rapidly. When ρ_c reaches 2.5×10^{10}g cm^{-3}, the oxygen deflagration is ignited and incinerates the material into nuclear statistical equilibrium (NSE) elements. However, electron captures are sufficiently rapid for the core to continue to collapse (see also Miyaji et al. 1980).

3) Preliminary calculation of the further collapse has been carried out up to the neutrino trapping density by adopting the equation of state by Wolff (1982) and the electron capture rates by Fuller et al. (1982). At $\rho_c = 3 \times 10^{11}$g cm^{-3}, entropy per nucleon and Y_e at the center are s = 1.2 k and $Y_e = 0.35$, the average Y_e over 0.8 $M_\odot$ is 0.43, and the mass of the NSE core behind the oxygen deflagration front is 0.52 $M_\odot$.

4) The hydrodynamical behavior of the core bounce and shock propagation might be somewhat different from the iron core of massive stars: The shock wave could be strengthened by the steep density gradient near the He-burning shell at $M_r = 1.375\ M_\odot$ (see Hillebrandt 1982) and might eject only the He layer to leave a neutron star behind.

4. CARBON ABUNDANCE OF THE EJECTED HELIUM LAYER

The final fate of the 8-12 $M_\odot$ star is probably Type II supernova explosion which leaves a neutron star behind. If the neutron star mass of 1.4 $M_\odot$ is assumed, ejected remnant should not contain much heavy elements as seen from M_{He} in Table. As discussed in the next section, the chemical composition of the He layer of these stars is particularly important to identify the Crab Nebula's progenitor:

1) For stars of $M \gtrsim 9.5\ M_\odot$, the carbon abundance of the helium layer is so high as $X_C \sim 0.03$-0.05 because the He shell burning is so active as to develop a convective shell (see Figures 2 and 3). Abundances of ^{14}N and ^{16}O are $X_N \sim X_O \sim 0.005$. (Hereafter X denotes the mass fraction.)

2) For $M \lesssim 9\ M_\odot$, the carbon abundance is not large because the dredging-up of the He layer prevents the convective He burning shell from developing (Figure 4). Such a mixing of H/He layer could produce a He-rich envelope if the mass loss would reduce the stellar mass down to $\sim 3.5\ M_\odot$ before the dredge-up. The resultant composition in the He-rich envelope would be $X_C \sim X_N \sim X_O \sim 0.004$ for $M_{H,0} = 2.2\ M_\odot$ model.

5. COMPARISON WITH THE ABUNDANCES OF THE CRAB NEBULA

According to the recent optical, IUE and IR observations (Henry and MacAlpine 1982; Davidson 1979; Davidson et al. 1982; Dennefeld and Andrillat 1981), the Crab Nebula has a helium overabundance of $1.6 \lesssim X_{He}/X_H \lesssim 8$, relatively small oxygen abundance of $X_O \sim 0.003$, and the carbon-to-oxygen ratio of $0.4 \lesssim X_C/X_O \lesssim 1.1$. The small oxygen abundance implies that only the hydrogen-rich envelope and the helium layer above the helium-burning shell was ejected and the lower layer must have formed the neutron star. The small carbon abundance is inconsistent with the stellar models for $M > 9.5\ M_\odot$ while it is consistent with $M \lesssim 9\ M_\odot$.

(Since all 8-12 $M_\odot$ models show ^{14}N overabundance in the He layer, ^{14}N abundance determination is also important. Fesen and Kirshner, 1982, suggested that ^{14}N may be overabundant; see, however, Dennefeld and Pequignot 1982, this conference.)

Based on the above discussion, the 8-9.5 $M_\odot$ star has been proposed to be the Crab Nebula's progenitor. The scenario of the post main-sequence evolution is as follows (see Nomoto 1982 and Nomoto et al. 1982 for details): During the red supergiant phase, the star lost 5-6 $M_\odot$ of its H-rich envelope by a stellar wind ($\dot{M} \sim 10^{-6} M_\odot\ y^{-1}$). During the C-burning, a He-rich envelope with $X_C/X_O \lesssim 1$ was formed by the mixing between the H-rich and He layer. After the C-burning, the O+Ne+Mg core was formed and finally collapsed by the electron captures. The bouncing shock wave was not strong enough to eject the core, but it was strong enough to eject the loosely bound He-rich envelope. The weak shock wave and the composition of the ejected matter was consistent with many of the observed features of the Crab Nebula. The suggested abundance variations among the filaments could be due to the partial mixing of the ejected material with the previously lost circumstellar material.

I would like to thank Drs. W.M. Sparks, R.A. Fesen, T.R. Gull, S. Miyaji, and D. Sugimoto for discussion on the Crab's progenitor (see Nomoto et al. 1982). Part of the calculation was carried out at Max-Planck-Institut. It is a pleasure to thank Prof. R. Kippenhahn for hospitality, Dr. W. Hillebrandt and Mr. R.G. Wolff for discussion on the core collapse, and H. Nomoto for preparation of the manuscript and figures.

REFERENCES

Boozer, A.H., Joss, P.C., and Salpeter, E.E. 1973, Ap.J. 181, 393.
Davidson, K. 1979, Ap.J., 228, 179.
Davidson, K., Gull, T.R., Maran, S.P., Stecher, T.P., Fesen, R.A., Parise, R.A., Harvel, C.A., Kafatos, M. and Trimble, V.L. 1982, Ap.J., 253, 696.
Dennefeld, M., and Andrillat, Y. 1981, Astron. Ap., 103, 44.
Fesen, R.A., and Kirshner, R.P. 1982, Ap.J., 258, 1.
Fuller, G.M., Fowler, W.A., and Newman, M.J. 1982, Ap.J. Suppl., 48, 279.
Henry, R.C., and MacAlpine, G.M. 1982, Ap.J., 258, 11.
Hillebrandt, W. 1982, Astron. Ap., 110, L3.
Miyaji, S., Nomoto, K., Yokoi, K., and Sugimoto, D. 1980, Publ. Astron. Soc. Japan, 32, 303.
Nomoto, K. 1981, in Fundamental Problems in the Theory of Stellar Evolution, ed. D. Sugimoto et al. (Reidel), p.295.
Nomoto, K. 1982, in Supernovae: A Survey of Current Research, ed. M.J. Rees and R.J. Stoneham (Reidel), p.205.
Nomoto, K., Sparks, W.M., Fesen, R.A., Gull, T.R., Miyaji, S., and Sugimoto, D. 1982, Nature, in press.
Wolff, R.G. 1982, private communication.
Woosley, S.E., Weaver, T.A., and Taam, R.E. 1980, in Type I Supernovae, ed. J.C. Wheeler (Univ. of Texas), p.96.