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Technical Memorandum 82179

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(NASA-TM-82179) THE ORIGIN OF THE CRAB
NEBULA AND THE ELECTRON CAPTURE SUPERNOVA IN
8-10 M_{\odot} SOLAR MASS STARS (NASA) 11 P
HC A02/MF A01

N81-32097

Unclas
G3/89 35613

CSCL 03A

JULY 1981

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

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To be published in the proceedings of
the NATO Advanced Study Institute on "SUPERNOVAE"
Institute of Astronomy, Cambridge, England
June 29 - July 10, 1981

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ABSTRACT

The chemical composition of the Crab Nebula is compared with several presupernova models. The small carbon and oxygen abundances in the helium-rich nebula are consistent with only the presupernova model of the star whose main-sequence mass was $M_{\text{ms}} \approx 8-9.5 M_{\odot}$. More massive stars contain too much carbon in the helium layer and smaller mass stars do not leave neutron stars. The progenitor star of the Crab Nebula lost appreciable part of the hydrogen-rich envelope before the hydrogen-rich and helium layers were mixed by convection. Finally it exploded as the electron capture supernova; the O+Ne+Mg core collapsed to form a neutron star and only the extended helium-rich envelope was ejected by the weak shock wave.

1. INTRODUCTION

The Crab Nebula is the remnant of the supernova in 1054 (SN 1054). It contains a pulsar which has provided a solid evidence for the neutron star formation through the supernova explosion. Therefore, it is quite important to answer the questions what was the progenitor star of SN 1054 and what was the mechanism of explosion. However, the origin of the Crab Nebula has been obscure despite a lot of observations.

In this paper, I discuss these questions from the point of view of chemical composition of the Crab Nebula. Based on the recent IUE observations (5) and the new theoretical work on the evolution of 8-10 M_{\odot} stars (11), I argue that SN 1054 was the electron capture supernova in the star which had a mass of 8-9.5 M_{\odot} on the zero-age main-sequence.

2. CHEMICAL COMPOSITION OF THE CRAB NEBULA

Many optical observations (4) and the recent UV observations with the IUE (5) have determined the chemical composition of the Crab Nebula. The abundances of hydrogen, helium, carbon, and oxygen and also the mass of the nebula are summarized as follows (X_H , X_{He} , X_C , and X_O denote their mass fractions):

- i) The Crab Nebula is helium-rich, i.e., $1.6 \lesssim X_{He}/X_H \lesssim 8$ (7); hydrogen and helium are distributed through the nebula and certainly are not well segregated (5).
- ii) Oxygen abundance is less than solar, i.e., $X_O \sim 0.003$, and oxygen-to-hydrogen ratio is roughly solar (5).
- iii) Carbon-to-oxygen ratio is $0.4 \lesssim X_C/X_O \lesssim 1.1$ (5).
- iv) The mass of the Crab Nebula is larger than $1.2 M_\odot$ (7) and probably around $2-3 M_\odot$ (5).

Since the Crab Nebula consists mostly of the ejecta of SN 1054 rather than the interstellar materials, its composition provides the important clue to determine the presupernova model of SN 1054 as will be discussed in the following sections.

3. COMPARISON WITH MASSIVE STAR MODELS OF $M \gtrsim 10 M_\odot$

High helium abundance and low oxygen abundance of the Crab Nebula imply that only the hydrogen(H)-rich envelope and helium (He) layer of the progenitor star were ejected to form the nebula (1), because there is an oxygen-rich layer just below the He-burning shell. This also implies that the materials contained below the He-burning shell should collapse into the neutron star. (Hereafter, M_H , M_{He} and M_C denote the mass contained interior to the burning shell of hydrogen, helium, and carbon, respectively, and M_{ms} denotes the stellar mass at the zero-age main-sequence.) The values of M_{He} at the presupernova stage for stars of $M_{ms} \gtrsim 10 M_\odot$ are $M_{He} = 2.6-1.8 M_\odot$ for $M_{ms} = 14-15 M_\odot$ (1, 15, 17);

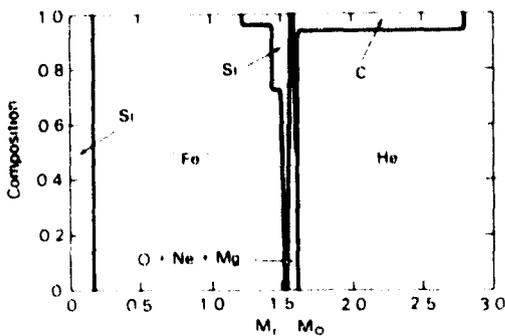


Figure 1: Composition of $\sim 12 M_\odot$ star ($M_H=3M_\odot$) at presupernova stage (onset of silicon flash).

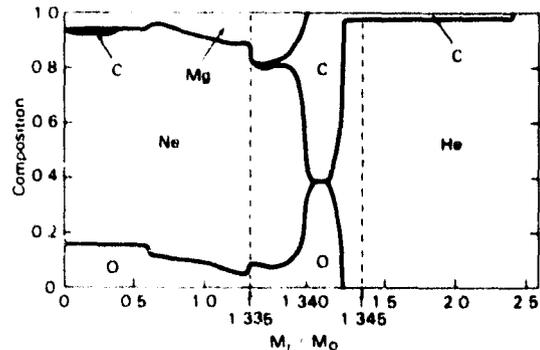


Figure 2: Composition of $\sim 9.5 M_\odot$ star ($M_H=2.6M_\odot$) at the onset of the dredging up of helium layer.

1.6 M_{\odot} for $M_{\text{ms}} \sim 12 M_{\odot}$ (10); 1.55 M_{\odot} for $M_{\text{ms}} = 10 M_{\odot}$ (20). Composition of $M_{\text{ms}} \sim 12 M_{\odot}$ star ($M_{\text{H}} = 3 M_{\odot}$) is shown in Figure 1.

If we assume the gravitational mass of the neutron star to be around 1.4 M_{\odot} , the progenitor models with $M_{\text{ms}} > 15 M_{\odot}$ may be inadequate because oxygen-rich material would be ejected, and probably $M_{\text{ms}} \lesssim 12 M_{\odot}$ is required for the progenitor star.

The small carbon abundance gives more strict constraint on M_{ms} of the progenitor star. During the late stages of evolution of stars with $M_{\text{ms}} \gtrsim 10 M_{\odot}$, helium shell burning is so active that it forms a convective zone and produce appreciable amount of carbon in the He-layer. For stars of $M_{\text{ms}} = 12 M_{\odot}$ (Figure 1) and $10 M_{\odot}$ (20), X_{C} is 0.06 and 0.04, respectively, in the convective shell of He-layer (0.05 and 0.03 if averaged over the He-layer). Although X_{C} could be reduced at most by a factor of 2 due to the mixing with H-rich matter, it is still too large to be compatible with such a low carbon abundance as $X_{\text{C}} \lesssim 0.003$ in the Crab. Therefore we conclude that the progenitor star of SN 1054 should have M_{ms} smaller than $10 M_{\odot}$.

4. COMPARISON WITH 8-10 M_{\odot} STARS

The evolution of $M_{\text{ms}} = 8-10 M_{\odot}$ stars is essentially different from more massive stars, because strong electron-degeneracy sets in when O+Ne+Mg core is formed. The final fate of these stars are electron capture supernovae (8, 11), i.e., the O+Ne+Mg core collapses due to electron captures and a neutron star will be left after the explosion. Therefore, the star in this mass range is a potential candidate for the Crab's progenitor.

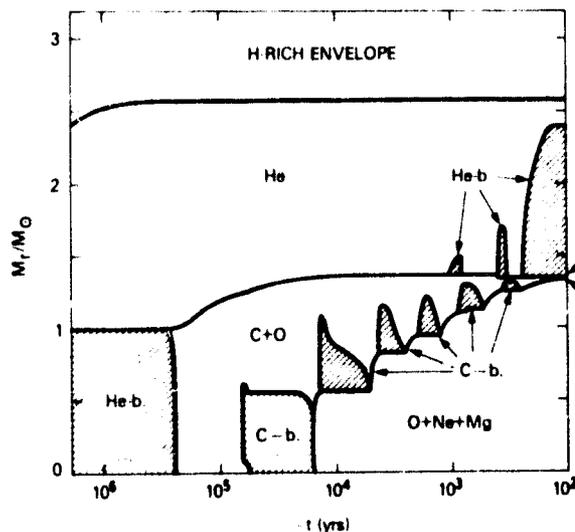


Figure 3: Chemical evolution of the core of $M_{\text{H}} = 2.6 M_{\odot}$

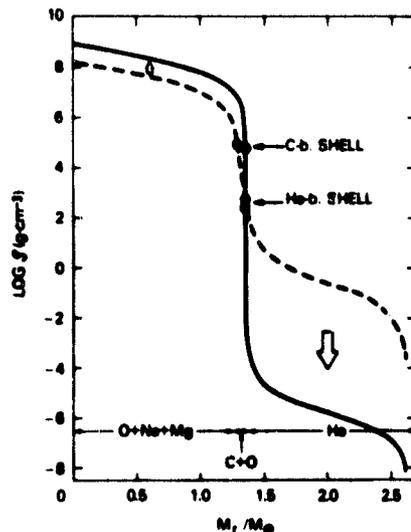


Figure 4: Expansion of the He-layer at $-t = 10^2$ yrs in Figure 3.

The composition of the supernova ejecta, in particular carbon abundance in the He-layer, depends on M_{ms} . I have computed the evolution of the helium core of 8-10 M_{\odot} stars systematically for $M_{\text{H}} = 2.4, 2.6$ and $2.8 M_{\odot}$ (9, 11). The evolution of the core of $M_{\text{H}} = 2.6 M_{\odot}$, which corresponds to $M_{\text{ms}} \sim 9.5-10 M_{\odot}$, is as follows (Figure 3): Carbon burning proceeds under non-degenerate condition. The resultant O+Ne+Mg core of mass M_{C} grows through the phases of several carbon-shell flashes. These shell flashes are too mild to induce any dynamical events. After a maximum temperature of $1.1 \times 10^9 \text{K}$ is attained in the outer shell, the temperature begins to decrease because of the neutrino loss. Neon ignition does not occur, because $M_{\text{He}} = 1.343 M_{\odot}$ is smaller than the critical mass of $1.37 M_{\odot}$ for the neon ignition. The electron degeneracy becomes stronger as M_{C} increases. When M_{C} reaches $1.339 M_{\odot}$ which is very close to $M_{\text{He}} (= 1.343 M_{\odot})$, the He-layer expands greatly as seen in Figure 4. This implies that the surface convection zone begins to penetrate into the He-layer and dredges up most of the materials in the He-layer.

As for the carbon abundance, the He-shell burning becomes active enough before the penetration of the surface convection zone so that carbon of $X_{\text{C}} = 0.03$ is produced in the convective shell of He-layer (shaded region in Figure 3; see also Figure 2 for the composition of this core at the onset of the dredging up of the He-layer). Therefore the star of $M_{\text{H}} = 2.6 M_{\odot}$ also contains too much carbon in the H-He envelope to be compatible with the small carbon abundance in the Crab Nebula.

However, such a carbon production in the He-layer is prevented for stars with slightly smaller M_{ms} , i.e., $M_{\text{ms}} \lesssim 9.5 M_{\odot}$ ($M_{\text{H}} < 2.6 M_{\odot}$): The preliminary results for the core of $M_{\text{H}} = 2.4 M_{\odot}$ shows that the penetration of the surface convection zone into the He-layer begins earlier than for the core of $M_{\text{H}} = 2.6 M_{\odot}$, i.e., at the early stages of carbon shell burnings (see also (18)) because of the stronger electron-degeneracy (see (16)). Most of the He-layer is dredged up before the He-shell burning becomes so active as to produce appreciable carbon. For stars with $8 M_{\odot} \lesssim M_{\text{ms}} \lesssim 9.5 M_{\odot}$, therefore, no carbon enrichment takes place in the H-He envelope at this stage.

5. EVOLUTION OF THE PROGENITOR STAR OF THE CRAB NEBULA

According to the discussions in the preceding sections, the following scenario of the evolution of the Crab's progenitor star is most plausible and consistent with the observations: On the zero-age main-sequence, the star had a mass of $M_{\text{ms}} \approx 8-9.5 M_{\odot}$. The star spent 3×10^7 yrs, 2×10^5 yrs, and 6×10^4 yrs for the H, He, and C burning phases, respectively. During the blue and red supergiant stages, the star lost $\sim 5-6 M_{\odot}$ of its envelope by mass loss to reduce the H-rich envelope mass down to $\sim 0.5-1 M_{\odot}$.

When the O+Ne+Mg core formed after the exhaustion of carbon in the central region, the surface convection zone penetrated into the He-layer and most of the materials in the He-layer ($\sim 1.2 M_{\odot}$) were dredged up into the H-rich envelope. At this stage, the H-He envelope had a mass of $\sim 2 M_{\odot}$ and had a composition of $X_H \sim 0.2-0.3$, $X_{He} \sim 0.8-0.7$, and a solar ratio of X_C/X_H and X_O/X_H . Since the He-layer had contained $\sim 1\%$ ^{14}N produced by the CNO cycle, ^{14}N abundance in the envelope was enhanced to as much as $X_N \sim 0.005$ by the mixing. (X_{He}/X_H and X_N depend on the mass ratio between the He-layer and H-rich envelope, i.e., on M_{MS} and mass loss rate. Also X_N is proportional to the initial CNO abundances.)

Afterwards the mass of the O+Ne+Mg core ($M_H \approx M_{He} \approx M_C$) increased from $\sim 1.3 M_{\odot}$ through $1.38 M_{\odot}$ due to triple shell-burnings of H, He, and C. During this phase, the carbon abundance in the envelope would be somewhat enhanced by the recurrence of the He-shell flashes in the thin He-zone and the associated dredging up of the processed material into the H-He envelope. Therefore X_C could be close to X_O in the presupernova envelope.

Finally the star became the electron capture supernova (8): At the stage with $M_C = 1.38 M_{\odot}$, the degenerate O+Ne+Mg core collapsed because the Chandrasekhar's limiting mass was reduced by electron captures on ^{24}Mg , ^{20}Ne , etc. During the collapse, the oxygen deflagration was ignited and incinerated the core materials into nuclear statistical equilibrium composition. Since the effects of electron captures dominated over the oxygen deflagration, the core continued to collapse.

Although the hydrodynamic behavior of the bounce of this core has not been investigated, from the recent computations of the collapse and bounce of the iron core, we would expect that the reflecting shock wave would not be strong enough to eject the core material. However, such a weak shock wave could eject the extended H-He envelope rather easily, because the shock wave would be strengthened due to the very steep density gradient around the core-envelope interface as seen in Figure 4 and because the binding energy of the extend envelope is as small as the order of 10^{46} erg.

Then the supernova ejecta consisted of the material of the He-rich envelope so that the composition was consistent with the Crab Nebula. This scenario predicts the enrichment of ^{14}N in the nebula; in fact, recent observations (6) suggest that ^{14}N may be overabundant. The interaction between the ejected He-rich envelope and the circumstellar H-rich material lost before the explosion might cause the suggested abundance variations among filaments (6).

Such a weak shock model is consistent with the small kinetic energy of expansion of the Crab Nebula. Also even the weak shock wave could produce the maximum luminosity of SN 1054 because the radius of the presupernova star would be as large as $\sim 10^{14}$ cm (3). The light curve at late times would be powered by the pulsar (13).

It should be noted that the progenitor model involving the star with $M_{\text{ms}} \sim 8 M_{\odot}$ ($M_{\text{H}} \sim 2 M_{\odot}$) is not adequate for the Crab because the star explodes completely as the carbon deflagration supernova (12) and does not leave a neutron star. Instead, helium stars of 1.5-2 M_{\odot} or C+O white dwarfs originating from stars of $M_{\text{ms}} \sim 8 M_{\odot}$ may become Type I supernovae as discussed in Appendix.

It is a pleasure to thank Drs. W. M. Sparks, R. A. Fesen, T. R. Gull, S. F. Maran, and T. P. Stecher for useful discussions and to H. Nomoto for preparation of the manuscript. This work has been supported by NRC-NASA research associateships in 1979-1981.

APPENDIX

CARBON DEFLAGRATION IN HELIUM STARS AND TYPE I SUPERNOVAE

Observations of Type I supernovae (SN I) has shown that their progenitor stars should be hydrogen-deficient and produce a large amount of ^{56}Ni through the explosion (19). It has been shown that supernovae in accreting white dwarfs satisfy these constraints (9, 11, 18, 20). Here I demonstrate that helium stars of 1.5-2.0 M_{\odot} also evolve into supernovae to produce a large amount of ^{56}Ni . Such low mass helium stars may form from the stars of $M_{\text{ms}} \approx 6-8 M_{\odot}$ if they lose the H-rich envelope by mass loss before the surface convection zone dredges up the He-layer.

The evolution of 2 M_{\odot} helium star is computed from the beginning of the helium burning. It forms a C+O core whose mass, M_{He} , grows by the helium shell burning. When M_{He} reaches $\sim 1 M_{\odot}$ and electrons become strongly degenerate, the helium envelope expands greatly as seen from the drastic change in the density distribution in Figure 5 (see also (14)). Afterwards the star moves upward along the Hayashi line in the HR diagram as M_{He} increases.

Since M_{He} grows at such a high rate as $4-6 \times 10^{-6} M_{\odot} \text{yr}^{-1}$, the resultant compressional heating ignites several carbon-shell flashes. Thus the C+Ne+Mg zone forms in the outer layers of the core (i.e., $M_{\text{r}} \sim 1.1 M_{\odot}$). Also the luminosity due to the gravitational energy release by the core compression is as high as the luminosity due to the He-shell burning.

Because of such a rapid growth of the core, carbon is ignited in the center at the stage with $M_{\text{He}} = 1.36 M_{\odot}$ and the central density of $\rho_c = 1.5 \times 10^9 \text{ g cm}^{-3}$; this is earlier than the degenerate carbon ignition in the normal stars (16). The carbon flash grows into the deflagration.

The carbon deflagration wave (DFW) propagates due to convective heat transport. Its hydrodynamical behavior is computed by the same method as in (12) for several parameters involved in the propagation velocity of the DFW, v_{def} . For the case with $v_{\text{def}} \sim 0.3 v_s$ (where v_s denoted the sound velocity behind the DFW), the propagation of the DFW is shown by the change in the temperature distribution in Figure 6.

As the DFW propagates, it becomes weaker, i.e., the temperature and density at the DFW decrease because of the core expansion. In the outer layer, moreover, the carbon deflagration changes into neon deflagration which is weaker because of smaller nuclear energy release.

Accordingly, the material in the inner layer of $0.90 M_{\odot}$ is incinerated into ^{56}Ni while $0.38 M_{\odot}$ Ca-Si-Mg-O are synthesized by the partial burnings of Si, O, and Ne in the decaying DFW. The rest, $0.08 M_{\odot}$ O+Ne+Mg, remains unburned.

The mass of ^{56}Ni , M_{Ni} , synthesized in the DFW depends on v_{def} : For $v_{\text{def}} \sim 0.5 v_s$, the core material is almost completely

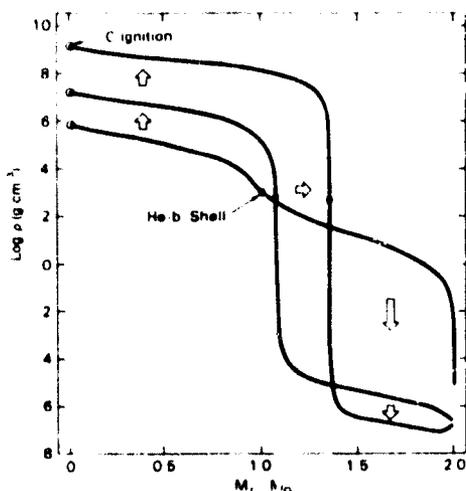


Figure 5: Evolutionary change in the density distribution. As the C+O core grows, the He-layer expands to form a red-giant-like envelope.

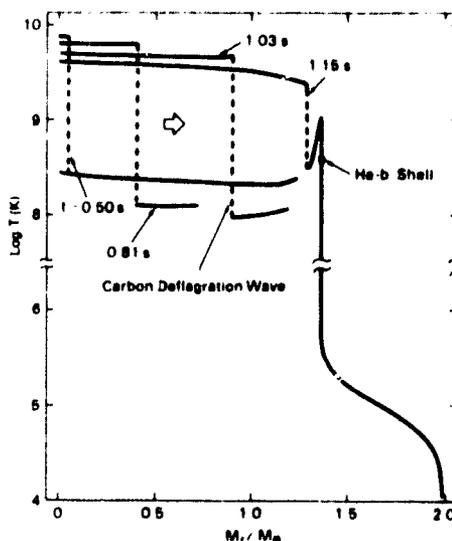


Figure 6: Propagation of the carbon deflagration wave and the associated change in the temperature profile.

incinerated into ^{56}Ni , i.e., $M_{\text{Ni}} \approx 1.36 M_{\odot}$, while $M_{\text{Ni}} \approx 0.7 M_{\odot}$ for $v_{\text{def}} \sim 0.25 v_{\text{s}}$.

We note: i) The carbon/neon deflagration in the helium star produces sufficient amount of ^{56}Ni to power the light curve of SN I by the radioactive decay of $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ (19). ii) Since this star has an extended helium envelope with the radius of $\sim 10^{13}$ cm (Figure 5), the rapidly expanding core hits the envelope and forms a very strong shock wave near the core-envelope interface. Such a shock wave may contribute somewhat to the SN I light curve (19). iii) The synthesis of Ca-Si-Mg-O in the outer layer leads to a surface composition consistent with the recent observation of SN I 1981 in NGC 4536 (2); the spectrum of this SN I at maximum light is well interpreted by the presence of Ca, Si, S, Mg, and O.

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