

WHITE DWARF MODELS FOR TYPE I SUPERNOVAE AND QUIET SUPERNOVAE,
AND PRESUPERNOVA EVOLUTION

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ABSTRACT

Supernova mechanisms in accreting white dwarfs (WDs) are presented, i.e., the carbon deflagration as a plausible mechanism for producing Type I supernovae and electron captures to form quiet supernovae leaving neutron stars. These outcomes depend on accretion rate of helium, initial mass and composition of the WD. The various types of hydrogen shell-burning in the presupernova stage are also discussed.

1. INTRODUCTION

Supernova explosions in mass-accreting white dwarfs (WDs) are thought to be a plausible mechanism for the Type I supernovae (SN I) (Finzi and Wolf, 1967). Recently, Arnett (1979) and Colgate et al. (1980) have shown that the light curves of SN I can be reproduced well by the radioactive decay model (${}^{56}\text{Ni} \rightarrow {}^{56}\text{Co} \rightarrow {}^{56}\text{Fe}$). The white dwarf models for SN I (Chevalier 1980) require 1.0 - 1.4 M_{\odot} of ${}^{56}\text{Ni}$ to explain the peak luminosity by the radioactive decay. Such an amount implies that almost all of the mass of the WD is processed into ${}^{56}\text{Ni}$ and ejected, i.e., no neutron star is left; this could be a detonation or deflagration type supernova.

On the other hand, the interpretation of the origin of some low mass X-ray binaries may require that some classes of accreting WDs collapse to form neutron stars (e.g. van den Heuvel, 1977). Such an event could be called a quiet supernova because the ejected mass may be negligibly small.

Whether the accreting WD explodes as a SN I or collapses to form a neutron star depends on the parameters involved, i.e., mass accretion rate, initial mass and composition of the WD, etc. The aim of the present paper is to clarify the relationship between the supernova mechanism

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and the conditions in the binary system based on the results of hydrodynamical computations for the whole evolutionary processes of the accreting C+O WDs through the supernova stages.

2. ACCRETION ONTO C+O WHITE DWARFS

In some cases of accretion onto C+O or O+Ne+Mg WDs, the helium zone is built up on the core as a result of steady burnings or weak flashes of hydrogen as will be discussed in section 5. I investigated such evolution of the C+O WDs by computing a steady accretion of helium through the supernova explosion for several cases of accretion rate dM/dt , and initial mass M_{C+O} , as summarized in Table 1. (See also Fujimoto and Sugimoto (1979) and Taam (1980a, b) for the quasi-static phases.)

When a certain amount of helium, ΔM_{He} , is accumulated, helium is ignited off-center at the density of ρ_{He} (Cases A-C) as summarized in Table 1. Such an ignition is determined by the thermal history of the

Table 1. Physical Quantities at the Ignition and Explosion.

Case	dM/dt ($M_{\odot}y^{-1}$)	M_{C+O} (M_{\odot})	ΔM_{He} (M_{\odot})	ρ_{He} ($g\ cm^{-3}$)	q/u_0	E_{expl} (erg)
A	3×10^{-8}	1.08	0.08	2.8×10^6	17	1.5×10^{51}
B	3×10^{-9}	1.08	0.23	3.6×10^7	3	1.9×10^{51}
C	7×10^{-10}	1.28	0.12	2.4×10^8	1	---
D	4×10^{-10}	1.28	0.12	(carbon ignition)		

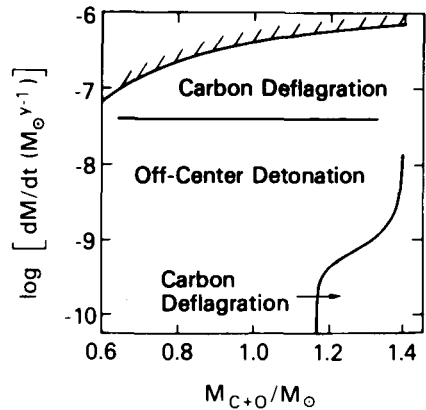
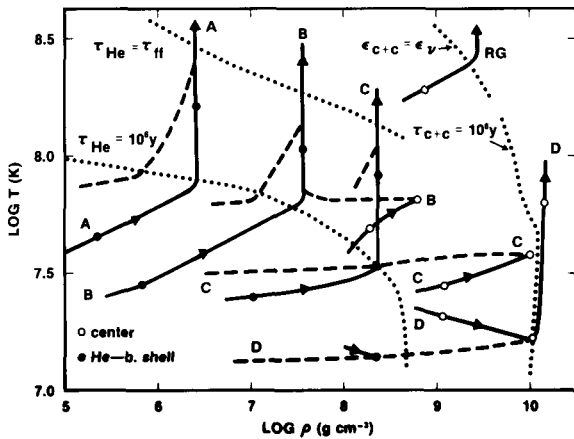


Fig. 1 Evolutionary paths (solid) and structure lines (dashed) of accreting WD.

Fig 2. Supernova mechanisms in WDs. In stead of carbon deflagration, electron capture SN occurs for O+Ne+Mg WD.

accretion, i.e., competition between the compressional heating due to accretion and the radiative cooling (Nomoto and Sugimoto 1977). This is clearly seen in Figure 1 where the evolutionary paths of the bottom of the accreted helium envelope (dashed) and the center of the WD (solid) in the density (ρ)-temperature (T) plane are shown. Also the ignition lines for helium and carbon defined by $T_n \equiv c_p T / \epsilon_n = 10^6 \text{ y}$ and $\epsilon_n = \epsilon_V$ are shown by dotted lines (see the notations in Sugimoto and Nomoto 1980). For the slower accretion, the temperature in the helium zone is lower, and the ignition of helium is delayed to higher ρ_{He} . Because of such a dependence of ρ_{He} on dM/dt , accretion onto the WD gives rise to a supernova explosion in the following three ways.

(1) Carbon deflagration for rapid accretion: When $dM/dt \lesssim 4 \times 10^{-8} M_{\odot} \text{ y}^{-1}$, ρ_{He} is lower than $3 \times 10^5 \text{ g cm}^{-3}$ so that the helium shell-flash is too weak to induce any dynamical effects (Nomoto and Sugimoto 1977; Fujimoto and Sugimoto 1979; Taam 1980a). The helium flashes will recur many times and, as a result, the mass of the C+O WD grows. Such an evolution is very similar to the growth of the C+O core in red giant stars so that the WD will explode as a carbon deflagration supernova (SN).

(2) Off-center dual detonations for the intermediate accretion rate: Cases A and B in Table 1 correspond to this case. Because of high ρ_{He} , the helium flash is so strong as to form the dual detonation waves of helium and carbon, propagating both outward and inward, respectively.

(3) Carbon deflagration or helium envelope-detonation for the slow accretion: When $dM/dt \lesssim 1 \times 10^{-9} M_{\odot} \text{ y}^{-1}$, ignition of helium takes place under the pycno-nuclear regime, i.e., it depends mainly on the density due to large enhancement by the strong screening effect. Then the result depends mainly on $M_{\text{C+O}}$ rather than dM/dt . In Case D, ρ_{He} does not reach the ignition line of helium until after the carbon is ignited in the center (Figure 1). If $M_{\text{C+O}} \lesssim 1.1 M_{\odot}$ at the same accretion rate, ΔM_{He} is large enough for the helium ignition to occur prior to the carbon ignition. Case C shows helium ignition at such high density. In this case, the helium detonation wave (DW) forms but carbon DW does not.

These dependences of the outcome on dM/dt and $M_{\text{C+O}}$ are summarized in Figure 2. [Taam (1980b) did not take into account the pycno-nuclear regime of helium ignition and so did not find the $M_{\text{C+O}}$ dependence.]

3. DEFLAGRATION AND DETONATION TYPE EXPLOSIONS AND MODELS FOR TYPE I SUPERNOVAE

Hydrodynamic behavior of the off-center detonations and the carbon deflagration models are summarized as follows. (Details are seen in Nomoto 1980a, b.) An important quantity to determine the behavior is the ratio q/u_0 given in Table 1 where q is the nuclear energy release by incineration and u_0 is the initial internal energy of the matter.

Dual detonation type supernovae: In Cases A and B, q/u_0 is large enough

to form the dual DWs of helium and carbon, which incinerate almost all materials into ^{56}Ni (see also Woosley et al. 1980). The WD is disrupted completely with the explosion energy, E_{expl} in Table 1, ejecting the materials composed almost exclusively of ^{56}Ni .

Helium envelope-detonation: In Case C, q/u_0 is rather low. The He-DW forms and incinerates most of the accreted helium into ^{56}Ni , but the C-DW does not form and the C+O core remains unburned. Since the initial binding energy of the helium zone is slightly larger than the nuclear energy release, some amount of ^{56}Ni could remain bound on the C+O core, while a part of it could be ejected. During the subsequent phase of helium accretion, ^{56}Ni will decay into ^{56}Co and ^{56}Fe . Therefore, this WD would have Fe and He in its envelope when a supernova explosion is triggered by the carbon ignition.

Carbon deflagration supernovae: The deflagration wave propagates at a subsonic speed of v_{def} by convective energy transport. The WD expands appreciably at later times, which makes the deflagration weaker and quenches the nuclear burning (Nomoto et al. 1976). Although the WD is completely disrupted with $E_{\text{expl}} = 1.3 \times 10^{51}$ erg for the case of $v_{\text{def}} \approx 0.2 v_s$ (v_s denotes the sound velocity), the ejecta is not exclusively composed of iron but include $0.28 M_{\odot}$ of Ca, S, Si, Ne, O, etc., which are synthesized by the partial burnings in the decaying deflagration wave. Other elements are $1.01 M_{\odot}$ of iron peak elements and $0.1 M_{\odot}$ of unburned C+O (Nomoto et al. 1976). If the slow accretion has occurred, it would also contain unburned He. Moreover, these elements are partly mixed by convection behind the propagating deflagration wave.

Observational constraints on models for SN I: Both detonation and deflagration type supernovae produce large amounts of ^{56}Ni which can provide a sufficient amount of radioactive energy for the peak luminosity and exponential tail of SN I. In particular, Chevalier showed that the carbon deflagration model of $v_{\text{def}} \approx 0.2 v_s$ (Nomoto et al. 1976) reproduce well the observational light curve.

The chemical compositions in the outer layers of SN I 1972e are being analyzed by Branch (1980). According to his preliminary results, the most plausible interpretation is that its outer layers consisted of a mixture of Na, Ca, Si, Fe, and probably He with higher abundances than solar. The upper limit of the Co/Fe ratio was estimated to be about 0.1.

This abundance feature is difficult to interpret by the detonation type model but can be explained qualitatively by the carbon deflagration model (Chevalier 1980). The probable existence of He and low Co/Fe ratio could be explained by the model of slow accretion like Case C.

4. O+Ne+Mg WHITE DWARFS AND ORIGIN OF QUIET SUPERNOVAE

Despite the plausibility of carbon deflagration models for SN I, whether the C+O WD collapses or explodes (for the slow accretion, in particular) is still debated.

If we consider the O+Ne+Mg WD, however, it has been clearly shown that this WD collapses due to electron captures on ^{24}Mg and ^{20}Ne despite

the competing oxygen deflagration (Miyaji et al. 1980; Nomoto et al. 1979b) as its mass grows close to the Chandrasekhar limit, M_{Ch} . Then a neutron star is formed. Such a O+Ne+Mg WD is formed from a 8-10 M_{\odot} primary star in a binary system, which loses its hydrogen and helium envelope by the Roche lobe overflow (Nomoto 1980a). Therefore, almost the same region of $(dM/dt, M_{WD})$ in Figure 2 as for the carbon deflagration corresponds to the origin of the quiet SN leaving neutron stars.

5. PRESUPERNOVA WHITE DWARFS

White dwarf models for supernovae (Figure 2) increase their masses, M_{WD} , toward the Chandrasekhar limit by building up a helium zone. In some cases of accretion, however, the hydrogen shell-flash could be so strong as to cause a large expansion leading to Roche lobe overflow and even a nova-like explosion; most of the accreted matter is then lost from the WD without producing much helium. Therefore, we need to clarify the conditions in binary systems under which M_{WD} can grow, i.e., the hydrogen shell-burning is steady or such a weak flash that the radius does not expand appreciably. Such conditions can be shown in the $(dM/dt - M_{WD})$ plane of Figure 3; building up of helium zone takes place in the following four cases.

- (1) Direct accretion of helium: If the companion star is an expanding helium star of 1.0 - 2.5 M_{\odot} (having a degenerate core of C+O or O+Ne+Mg) or a degenerate helium star (as a stripped core), then helium can be transferred directly from such a companion star. An observed example is G61-29 (Nather et al. 1979).
- (2) Steady hydrogen burning (CNO cycle): For a certain range of rather high accretion rate as indicated in Figure 3, stable and steady hydrogen

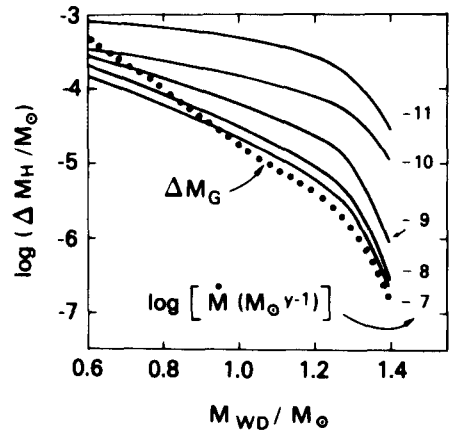
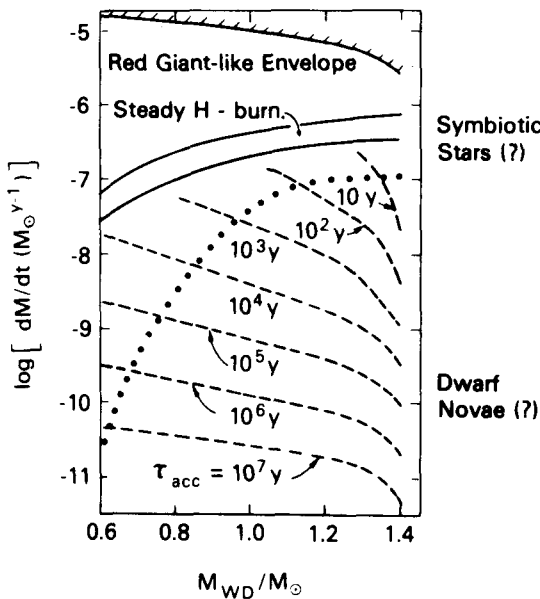


Fig. 4 Solid lines show ΔM_H at the ignition. See text for ΔM_G .

Fig. 3 Various types of hydrogen shell burnings.

burning occurs (Sienkiewicz 1980). For the accretion faster than the upper limit to this range, a red giant-like envelope is formed (Nomoto et al. 1979a). Paczyński and Rudak (1980) suggested that one type of symbiotic stars might be the white dwarfs burning hydrogen steadily. (3) Weak flash: When the hydrogen burning is unstable, the strength of the flash is weaker as the mass of the accreted hydrogen-rich matter, ΔM_H , is smaller. If ΔM_H is smaller than a certain limiting value of ΔM_G , the resulting expansion may be small, i.e., the radius may not exceed $0.5 R_\odot$ (see e.g. Shara et al. 1978). The value of ΔM_G is shown in Figure 4 as a function of M_{WD} , which is estimated from the steady burning WD models (Sienkiewicz 1975) and also from the stellar models evolving from red giants to WDs (Paczyński 1971); for such models, the radius varies from a WD to a red giant size depending sensitively on ΔM_H .

The value of ΔM_H at the hydrogen ignition is a function of (dM/dt , M_{WD}) as shown in Figure 4 and is taken from the models where the compressional heating due to accretion is just balanced with the radiative cooling (Nariai and Nomoto 1979); such a condition is realized after a few flash cycles. The accretion time, $\tau_{acc} \equiv \Delta M_H / (dM/dt)$, between the flashes is plotted in Figure 3. (Similar figures for ΔM_H and ΔM_G can be made approximately based on the semi-analytical theory; Fujimoto 1980.)

It is shown that, although ΔM_H is smaller for higher dM/dt , $\Delta M_H > \Delta M_G$ for massive WDs even with very rapid accretion. Then roughly $\Delta M_H - \Delta M_G$ of the accreted matter will be lost, and ΔM_G gives a rough estimate of mass which could be processed into helium. In Figure 3, the dotted line shows the value of dM/dt which corresponds to $\Delta M_G / \Delta M_H \sim 0.7$ indicating that an appreciable amount of helium could be produced in the region of higher dM/dt . Paczyński and Rudak (1980) suggested also that such a weak flash might be the cause of light variations in another type of symbiotic stars. The recurrence period of such flashes would be approximately equal to τ_{acc} shown in Figure 3.

(4) Steady hydrogen burning (p-p chain): When the accretion is as slow as $10^{-10} M_\odot y^{-1}$, the accretion time is $\tau_{acc} \sim 10^6 y$ as seen in Figure 3. Starrfield et al. (1980) suggested that diffusion of CNO nuclei out of the accreted matter could occur for such a long τ_{acc} (see e.g. Vauclair 1979) and lead to a stable burning by the proton-proton chain. Dwarf novae may correspond to such a low accretion rate. In fact, recent simultaneous observations of some cataclysmic variables (AM Her, U Gem, and SS Cyg) show a strong excess UV flux compared with the optical and X-ray fluxes, which might be originated from steady nuclear burning near the surface of WD (Fabbiano et al. 1980).

6. DISCUSSION

Triggering mechanisms for SN I and quiet SN in WDs are summarized in Figure 2, which depend on dM/dt , and initial mass and composition of the WD. In these models, the growth of M_{WD} toward M_{Ch} is required so that the hydrogen shell-burning in the presupernova stages must be stable or a very weak flash. Such a condition is realized for a rather rapid accretion ($dM/dt \sim 10^{-7} M_\odot y^{-1}$) or for a slow accretion ($dM/dt \sim 10^{-10} M_\odot y^{-1}$).

γ^{-1}) (Figure 3); the intermediate accretion rate between these two cases probably correspond to a nova-like explosion.

Such conditions for dM/dt might preclude the detonation type SN but correspond to the range in Figure 2 for which the carbon deflagration SN and the electron capture quiet SN are realized. This is consistent with the inability of the detonation model to account for the observed abundances in SN I ejecta.

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DISCUSSION

FALK: In the helium detonation, carbon deflagration model, you say you can get the iron out above the C-O but you make it as nickel. Branch does not see cobalt.

NOMOTO: We have, then, a very long accretion phase.

FALK: How long?

NOMOTO: 10^7 years.

FALK: What you are saying is that the detonation is not explosive in terms of the ejecta.

NOMOTO: This is because the μ gradient energy needed is more than the potential energy.

FALK: It pulses for awhile and deflagrates to throw the stuff off. Very cute.