Effects of a New Triple-α Reaction Rate on the Helium Ignition of Accreting White Dwarfs

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(Received September 30, 2010)

Effects of a new rate of the triple-α reaction on the ignition of a carbon-oxygen white dwarf accreting helium in a binary system have been investigated. The ignition points determine the properties of a thermonuclear explosion of a Type Ia supernova (SNIa). We examine the evolutionary tracks of white dwarfs with various accretion rates and initial masses. It is found that for all cases from slow to intermediate accretion rates, nuclear burnings are ignited at the helium layers. As a consequence, carbon deflagration would be triggered for the lower accretion rate than $dM/dt \simeq 4 \times 10^{-8} M_\odot \ \mathrm{yr}^{-1}$ which has been believed to the lower limit of the accretion rate for the deflagration supernova. Furthermore, the off-center helium detonation dominates the mechanism of SNIa for intermediate and slow accretion rates.

§1. Introduction

The triple-α (3α) reaction plays an important role for the helium burning stage on the stellar evolution of low, intermediate and high mass stars,[1)-3)] and accreting white dwarfs,[4),5)] where the 3α reaction has been written as a series of the following two reactions:

$$\alpha + \alpha \longrightarrow {}^{8}\mathrm{Be}, \qquad \alpha + {}^{8}\mathrm{Be} \longrightarrow {}^{12}\mathrm{C} + \gamma.$$

Recently, the reaction rate has been calculated,[6)] which is very large compared with the old rate[5),7),8)] used so far. It should be examined how the new rate affects astrophysical phenomena, because terrestrial experiments for the 3α reaction are very difficult such as the study on the QCD phase transition at high densities. We investigate the effects of a newly calculated 3α reaction rate (OKK rate)[6)] on the helium flashes, which takes place at the center or inside layers of the accreting envelope of the compact stars. The igniton curve is a fundamental criterion when the nuclear burning begins to occur and becomes the main energy source to change the stellar structure, where the fates of the massive stars and/or accreting white dwarfs are determined from the strength of specified nuclear burnings.[4),10)] While nuclear burning depends on the temperature severely, the density becomes very important at high density of $\rho \geq 10^6$ g cm^{-3} and low temperature of $T \leq 10^8$ K, because the screening effects begin to enhance the reaction rates.

It has already been shown that the new rate affects significantly the evolutionary tracks of low mass stars.[8)] The evolutions of 1 and 1.5 $M_\odot$ stars have been followed from the zero-age main sequence through the core He flash/burning. The HR diagram with use of the OKK rate disagrees considerably with the observations of low mass stars. It is found that the new rate results in the shortening or disappearence of the red giant phase, because helium ignites at a much lower temperature and density compared to the case with the old NACRE rate.[7] Consequently, the OKK rate could be not compatible with observations. If the new rate is right, we must invoke some new physical processes such as rotational mixing or other unknown physical effects.

On the other hand, abundances such as helium in globular clusters are open to dispute,[9] which may change the senario of the stellar evolution of low mass stars. We can see the effects of the OKK rate on the stellar evolution with use of the ignition properties. The helium core flash is triggered if the nuclear generation rates ε_n significantly overcome the neutrino loss rates ε_ν. Figure 1 shows the ignition curves of the 3α reaction. The solid line corresponds to the OKK rate and the dashed line is the old rate (labeled with Nomoto, which is equivalent to NACRE). Also shown are the evolutionary tracks of the central temperature T_c against the central density ρ_c for stars of 1 to 40 $M_\odot$ from the main sequence stages.[8),12),13] The evolutions are calculated beyond the core helium burning with the old 3α reaction rate. We can understand clearly that the helium ignition occurs at the points of considerably low temperature and density compared to the old cases.[1),11]

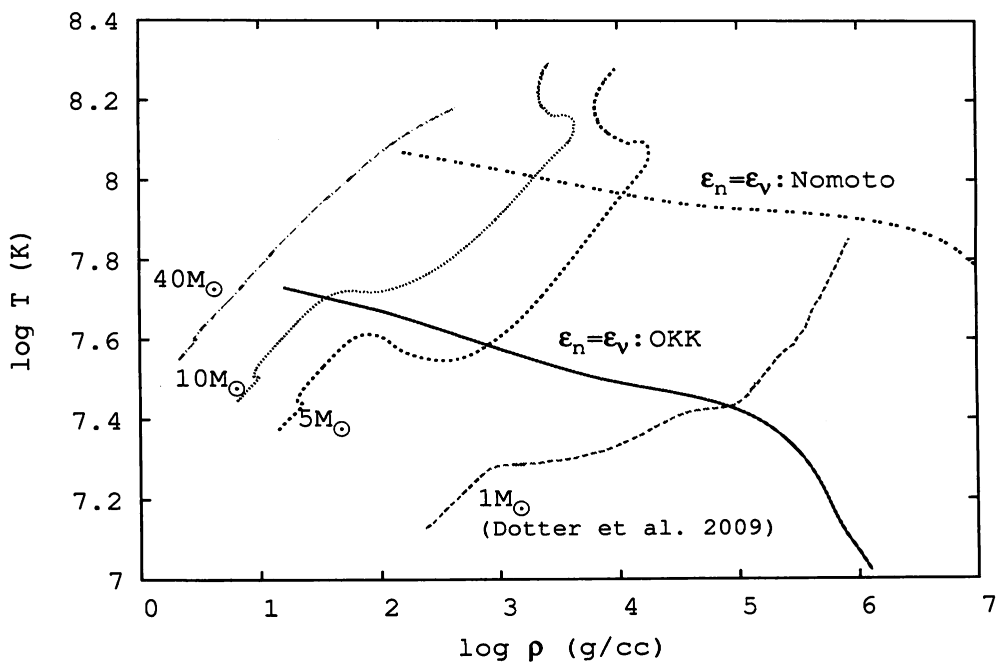

Fig. 1. Ignition curves $\varepsilon_n = \varepsilon_\nu$ for the 3α reaction. The solid line is due the OKK rate and the dashed line is the old rate. Evolutionary tracks of (ρ_c, T_c) with the old rate are indicated by the dottted curves for stars of 1–40 $M_\odot$ from the the zero-age main sequence stage.[8),12),13]

§2. Ignition curves and helium flash on the accreting white dwarfs

Accreting white dwarfs are considered to be the origin of the Type Ia supernova (SNIa) explosions.[11)] While the white dwarfs are composed mainly of carbon and oxygen (CO), accreting materials are usually hydrogen and/or helium. Since the hydrogen is converted to helium through steady hydrogen burning, helium is accumulated on the white dwarf gradually and the deep layers become hot and dense. Once the helium flash is triggered in a region composed of degenerate electrons, it could develop to the dynamical stage, which depends on the accretion rate dM/dt.[11)] The properties of ignition depend on the initial mass of the white dwarf $M_{\rm C+O}$ for slow accretion rates. When the accretion is rather rapid, $dM/dt \geq 4\times 10^{-8} M_\odot$ yr^{-1}, the carbon deflagration supernova is triggered at the center.[14)] The reactions crucial for the carbon ignition are

$$
{}^{12}{\rm C} + {}^{12}{\rm C} \longrightarrow \begin{cases} {}^{20}{\rm Ne} & + & \alpha, \\ {}^{23}{\rm Na} & + & {\rm p}, \\ {}^{24}{\rm Mg} & + & \gamma. \end{cases}
$$

Figure 2 shows the ignition curves concerning the helium flash on the accreting white dwarfs with the old and new 3α (OKK) reaction rates adopted, which gives (ρ_c, T_c) for the onset of the helium flashes. It is found[4)] that the ignition occurs on the condition of $\tau_n = 10^6$ yr, where the time scale of the temperature increase through the nuclear reaction is given by

$$
\tau_n = C_p T/\varepsilon_n, \tag{2.1}
$$

where C_p is the specific heat at constant pressure. The nuclear generation rate of the old 3α reaction is approximately expressed for high temperature regions as

$$
\varepsilon_n \simeq \frac{5\times 10^{21} f \rho_5 X^3}{T_8^3} \exp(-43.2/T_8) \quad {\rm erg\ g^{-1} s^{-1}}, \tag{2.2}
$$

where T_8 is the temperature in units of 10^8 K, ρ_5 is the density in 10^5 g cm^{-3}, f is the screening factor, and X is the helium mass fraction. Evolution of CO white dwarfs was computed[4)] by adopting the Heney-type implicit-explicit method[1)] from the hydrostatic evolutionary stage of accreting helium to the hydrodynamical stage of thermonuclear explosions. The evolutionary tracks of (ρ_c, T_c) are taken from the figures in Ref. 4). The values of $(M_{\rm C+O}\ (M_\odot), dM/dt\ (M_\odot\ {\rm yr}^{-1}))$ are as follows: (case A: 1.08, 3×10^{-8}), (case B: 1.08, 3×10^{-9}), (case C: 1.28 , 7×10^{-10}) (case D: 1.35 , 7×10^{-10}), (case E: 1.13, 4×10^{-10}) and (case F: 1.28, 4×10^{-10}). Since the convection begins to prevail at the beginning of helium burning, evaluation of the ignition point includes some uncertainties. Therefore, we consider two ignition curves of $\tau_n = 10^5$ and 10^7 yr for the OKK rate in Fig. 2 using the same method in Ref. 2). It has been shown that the OKK rate is large compared to NACRE by a factor of 10^{26} at $T_8 = 0.1$, 10^6 at $T_8 = 1$ and 1.9 at $T_8 = 2$. We can find that the helium ignitions occur at lower density by almost two orders of magnitude when the OKK rate is adopted. Contrary to the old results,[4)] the nuclear flashes are triggered

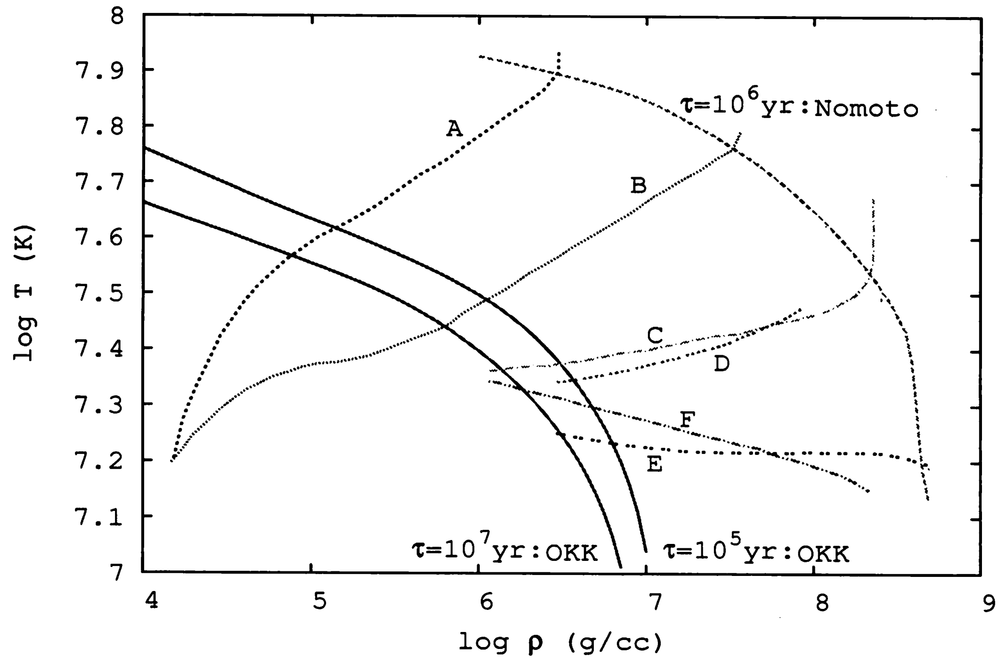

Fig. 2. Ignition curves specified by $\tau_n = C_pT/\varepsilon_n$ for the helium flashes on the accreting white dwarfs. The solid line is due the OKK rate with $\tau_n = 10^5$ and 10^7 yr and the dashed line is the old rate with $\tau_n = 10^6$ yr. The dotted curves are the evolutionary tracks[4)] of (ρ_c, T_c) with the old rate.

for all cases of A–F in the helium layers which are accumulated on the CO white dwarfs.

§3. Discussion and conclusions

The ignition densities that determine the triggering mechanism of SNIa will be changed drastically if we adopt a new 3α reaction rate. We note that the revised rate[15)] does not change qualitatively our conclusions, because the rate is not different compared to that of NACRE within a factor of 2 for the relevant range of temperature. Although it has been shown[4)] that the specific nonresonant 3α reaction is crucial in determining the helium ignition density for accretion as slow as $dM/dt \leq 10^{-9} M_\odot\ \mathrm{yr}^{-1}$, microscopic calculation for the three body problem is found to be much more important to evaluate the 3α reaction rate. Classification[4),5)] due to the accretion rate on the $dM/dt - M_{\mathrm{C+O}}$ plane will be changed significantly. It was found that when the density in the burning shell become higher than 2×10^6 g cm^{-3}, the nuclear flash grows into detonation or deflagration. We emphasize that the accretion rates which induce the carbon deflagration supernova become much lower compared to the standard rate of $dM/dt \simeq 4 \times 10^{-8} M_\odot\ \mathrm{yr}^{-1}$,[1),4),5),11),14)] because the ignition points for the cases C–D shift toward the density of 10^6 g cm^{-3} as seen in Fig. 2. Contrary to the old calculations, the off-center helium detonation dominates the mechanism of SNIa for the low helium accretion rate of $dM/dt \leq 7 \times 10^{-10} M_\odot$ yr^{-1} without the carbon ignition at the center.

We summarize the observational consequences of SNIa related to the new rate of 3α reaction.

1. Carbon deflagration model has succeeded in explaining the observations of SNIa. The fact[14] that the carbon deflagration occurs much more frequently compared to the simple detonation could be consistent with the new rate because accretion rates responsible for SNIa may become lower.

2. Concerning the nucleosynthesis of ^{56}Fe, ^{56}Ni, and Ca-O, the amounts of produced elements are not so different compared to W7(the rapid accretion model which leads to the initiation of the carbon deflagration at the center[14]). However, effects of the new rate on the nucleosynthesis is not clear, since it will need to calculate several models of lower accretion rates of $dM/dt \leq 4 \times 10^{-8} M_\odot$ yr^{-1}.

3. There are some observations that the light curves of SNIa cannot be explained by model W7. Thus many models different from W7 are proposed , which are related to the outer layer of exploding white dwarfs. For example, a late detonation model produces a lot of ^{56}Ni in the outer layer. Since the new rate affects the deflagration model through the accretion rates and layers, models such as the late detonation models would be modified.

The new rate affects also the helium ignition in accreting neutron stars. In particular, for lower accretion rates, helium burns at lower densities and temeratures, which could change the epoch of a formation of a helium detonation wave and a modeling of Type I X-ray bursts.[5] In particular, mechanism of superbursts should be studied again with use of the new rate, because the amount of ^{12}C plays a crucial role to induce the superbursts.[16]

Acknowledgements

We would like to thank S. Fujimoto for information about the new 3α reaction and relevant references. We appreciate H. Saio for the permission to use his stellar evolution code. This work has been supported in part by a Grant-in-Aid for Scientific Research (19104006, 21540272) of the Ministry of Education, Culture, Sports, Science and Technology of Japan.

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