

Is KPD 1930+2752 a good candidate type Ia supernova progenitor?

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Abstract. We investigate the evolution of a binary system which initially has an orbital period of $2^{\text{h}}17^{\text{m}}$ and contains a $0.5 M_{\odot}$ helium star with a white dwarf companion of $0.97 M_{\odot}$, similar to the suggested SN Ia candidate progenitor KPD 1930+2752. We show that the helium star completes core helium burning and becomes a white dwarf before the components merge. The most probable outcome of the merger of the components is the formation of a massive white dwarf, despite the fact that initially the total mass of the system is above the Chandrasekhar mass.

Key words. stars: evolution – stars: KPD 1930+2752 – stars: SNe Ia – binaries: evolution

1. Introduction

The double-degenerate (DD) model for progenitors of type Ia supernovae (Tutukov & Yungelson 1981; Webbink 1984; Iben & Tutukov 1984) considers a binary with the total mass of white dwarf components higher than the Chandrasekhar limit, which merges in less than Hubble time due to the loss of angular momentum via gravitational wave radiation. A type Ia supernova (SN Ia) is supposed to result from explosive carbon burning in the merger product. This model encounters two major problems: (i) none of the detected DD systems with sufficiently short orbital period has an estimated total mass of the components above the Chandrasekhar limit (see Maxted & Marsh 1999); (ii) it is not clear whether the carbon detonation may be initiated in the merger product.

The first of these problems has been attempted to be solved by systematic surveys for DD (e.g., the latest are by Saffer et al. 1998; Koester et al. 2001), which still didn't give definite results. The second problem still awaits numerical solution (see, e.g., Segretain et al. 1997).

In the meantime, helium-rich type B subdwarfs with white dwarf companions (sdB+wd systems) have been suggested as candidate SNe Ia progenitors (Saffer et al. 1998; Marsh 2000; Maxted et al. 2000). In particular, the star KPD 1930+2752 (Downes 1986) has attracted attention. High speed photometry (Billères et al. 2000) and

spectroscopy of the $H\alpha$ and HeI 6678 Å lines (Maxted et al. 2000) provide the evidence that this system is a binary with $P_{\text{orb}} = 2^{\text{h}}17^{\text{m}}$. Maxted et al. show that the total mass of the binary is at least $1.47 \pm 0.01 M_{\odot}$, if the sdB star has a “canonical” mass of hot subdwarfs of $0.5 M_{\odot}$. This makes, in their opinion, KPD 1930+2752 the first good candidate SN Ia progenitor.

In this Letter we discuss the possible evolution and fate of a system similar to KPD 1930+2752. In Sect. 2 we briefly consider the formation and overall features of sdB+wd systems, in Sect. 3 some details of our evolutionary code are described. Numerical results are given in Sect. 4. A discussion follows in Sect. 5.

2. Formation of low-mass helium star – white dwarf systems

One may start with an intermediate mass close binary: $M_1 \approx 5\text{--}10 M_{\odot}$, $M_2 \approx 2.5\text{--}5.0 M_{\odot}$. As a result of the Roche lobe overflow (RLOF) the primary component becomes a CO white dwarf. If the secondary experiences case B of RLOF, it becomes a $\sim(0.35\text{--}0.80) M_{\odot}$ helium star. In the core helium burning stage it settles in the region of the $\log T_{\text{eff}} - \log g$ diagram occupied by the stars which are spectroscopically classified as “subdwarf B stars”, but in the evolutionary status nomenclature are called “extreme horizontal branch stars” (EHB)¹.

¹ Maxted et al. (2001) specially notice this terminological distinction; we follow the “observational” notation – sdB.

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In another scenario for the formation of an sdB + wd system the secondary component of a close binary may be a $M_2 \lesssim 2.5 M_\odot$ star. If the secondary fills the Roche lobe when the mass of its helium core is still lower than but sufficiently close to the helium ignition limit ($\sim 0.45 M_\odot$ for the solar metallicity objects) the remnant of the secondary may ignite He in the core but it will never become an AGB star (D’Cruz et al. 1996).

Maxted et al. (2001) estimate that $69 \pm 9\%$ of all EHB stars are in short period binaries ($0.03\text{d} \lesssim P_{\text{orb}} \lesssim 10\text{d}$). Green et al. (2000) find that at least 2/3 of local disk sdB stars are binaries. Their survey suggests that most of them “with periods of the order of hours or a few days have essentially invisible companions”. It is natural to assume that these systems contain white dwarfs.

However, only a few systems have confirmed white dwarf components. Both orbital period and masses of components are known only for KPD 1930+2752 and KPD 0422+5421 (Orosz & Wade 1999) and only in KPD 1930+2752 is the total mass close to M_{Ch} .

Helium stars with $M \lesssim 0.8 M_\odot$ do not expand in the core helium burning stage (Paczynski 1971). In a wd+sdB system, if the core helium burning time $t_{\text{He}} \sim (1-2) \times 10^8$ yr is shorter than the merger time due to gravitational wave radiation

$$t_{\text{GR}} \approx 1.5 \times 10^8 a^4 M_1^{-1} M_2^{-1} (M_1 + M_2)^{-1} \text{ yr}, \quad (1)$$

where a is the orbital separation (in R_\odot), $M_{1,2}$ – the masses of components (in M_\odot), the helium star may evolve directly into a CO white dwarf. In the case of KPD 1930+2752 these two time scales, t_{He} and t_{GR} , are comparable and the fate of the system has to be explored numerically.

3. The evolutionary code

For the present study we applied an upgraded version of the evolutionary code which was used before for the calculation of the evolution of binaries with helium secondaries (Ergma & Fedorova 1990).

We have implemented the equation of state for the helium-rich matter given by Saumon et al. (1995) and for carbon by Fontaine et al. (1977). The helium burning rate has been estimated according to Caughlan et al. (1985). Neutrino losses have been calculated after Beaudet et al. (1967). We have used opacity tables of Iglesias & Rogers (1996) and Alexander & Ferguson (1994). The mass loss rate in the Roche lobe filling stage has been calculated following Kolb & Ritter (1990). The initial abundance of He in the model was assumed to be $Y_c = 0.98$, abundance of heavy elements $Z = 0.02$.

4. Results of calculations

To understand the fate of KPD 1930+2752 we have calculated the evolution of a $0.5 M_\odot$ helium star through the core helium burning stage.

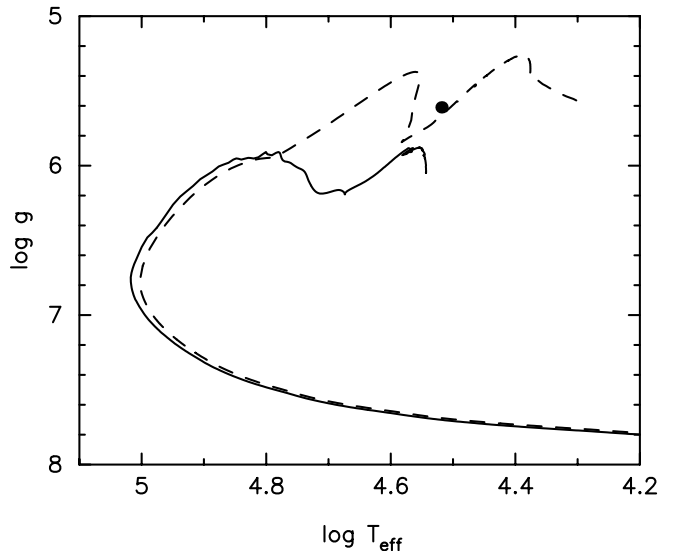


Fig. 1. Evolutionary track of a $0.5 M_\odot$ helium star in the $T_{\text{eff}} - \log g$ plane. Solid line is for pure helium star, dashed line is for a star which initially had $0.001 M_\odot$ hydrogen envelope. Heavy dot marks position of KPD 1930+2752.

For a pure helium $0.5 M_\odot$ star the effective temperature and surface gravity are higher than the measured $T_{\text{eff}} = 33\,000$ K and $\log g = 5.61$ for KPD 1930+2752. Both T_{eff} and g are slightly lower if the star has initially a low-mass hydrogen envelope ($< 0.001 M_\odot$), which is then lost during the core helium burning phase (Fig. 1)².

The helium in the core of the model was exhausted in $\sim 1.5 \times 10^8$ yr and a progenitor of a low mass carbon-oxygen white dwarf with a helium envelope was formed. The distribution of chemical species in the model upon completion of the helium burning is shown in Fig. 2.

It was assumed that the helium star has a $0.97 M_\odot$ companion and the initial $P_{\text{orb}} = 2^{\text{h}}17^{\text{m}}$. The variation of the separation of the components was then followed assuming the standard equation for the angular momentum loss via gravitational waves (Landau & Lifshitz 1971).

During the helium burning and subsequent cooling phases P_{orb} decreases due to gravitational wave radiation and at $P_{\text{orb}} \approx 1^{\text{m}}5$ the less massive white dwarf fills its Roche lobe. The following mass exchange stage is crucial for the fate of the system. This phase determines whether an SN Ia occurs. Two scenarios are possible.

4.1. Delayed merging scenario

White dwarfs overflowing their Roche lobe are subject to a dynamical instability if the mass ratio of components exceeds a certain critical value $\sim 2/3$ (Pringle & Webbink 1975; see also Han & Webbink 1999 and Nelemans et al. 2001 for the most recent discussion of stability and energetics of mass transfer in double white dwarfs). Mass exchange in a $0.5 M_\odot + 0.97 M_\odot$ binary

² One has also to bear in mind that the mass of the helium star in KPD 1930+2752 is *assigned* but not measured directly.

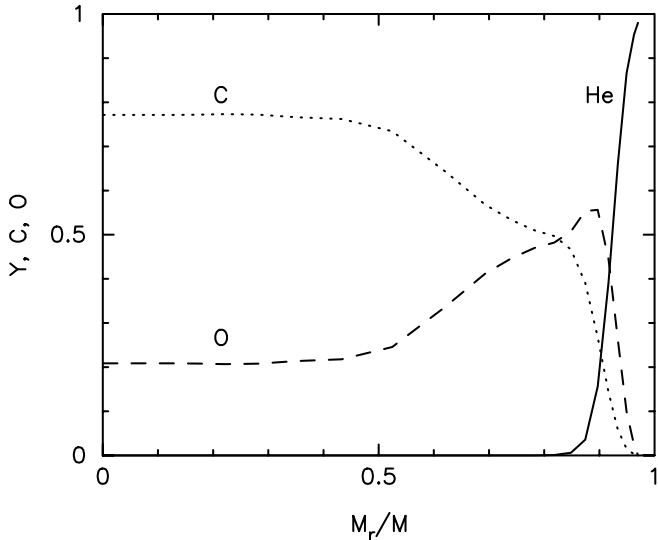


Fig. 2. Distribution of helium, carbon and oxygen in the nascent white dwarf formed by a $0.5 M_{\odot}$ helium star.

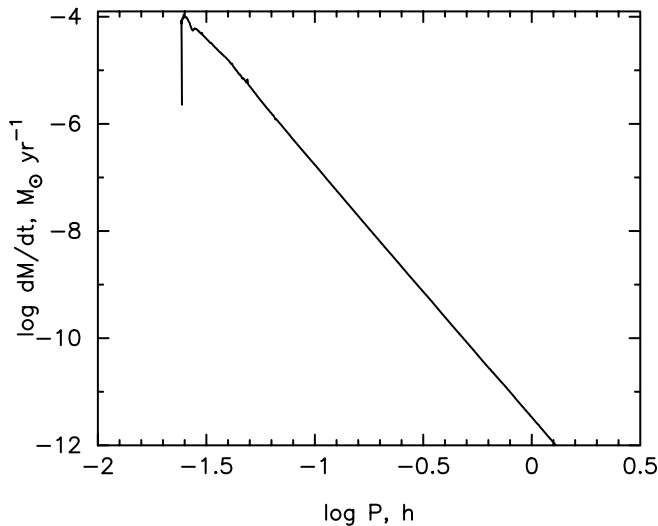


Fig. 3. Mass loss rate by the Roche-lobe filling white dwarf vs. orbital period of the binary.

white dwarf is expected to be dynamically stable, but \dot{M} has to exceed \dot{M}_{Edd} for a $0.97 M_{\odot}$ white dwarf. We assumed that the white dwarf accretes at the Eddington rate and that the excess of the matter is lost from the system with the specific angular momentum equal to that of the accretor. This gives an additional stabilising effect to the mass exchange. The dependence of the mass loss rate on the orbital period for our model system is shown in Fig. 3.

After $\sim 0.218 M_{\odot}$ is lost by the donor, the accretion rate decreases below \dot{M}_{Edd} . At the end of the mass transfer ($t = 10^{10}$ yr) orbital period has increased to $\sim 1^{\text{h}}3$ and the mass of the secondary became less than $0.007 M_{\odot}$. Although primary mass has grown to $1.33 M_{\odot}$ it remained below the limiting mass for the carbon burning.

However, the picture described above almost certainly oversimplifies the actual evolution. First, the liberated accretion energy has to be sufficient to evaporate the matter

from the distance of the order of the orbital separation of components. This requires $\dot{M}_2/\dot{M}_{\text{Edd}} \sim 10$, a condition which may be not fulfilled (Fig. 3). If this is the case, one may expect formation of a common envelope and the merger of components due to dissipative orbital energy losses. An R CrB type star may be formed in this way (Iben et al. 1996). Another complication is brought in by the presence of a He-rich layer atop the donor star (Fig. 2).

As our test calculations of accretion onto a white dwarf show, during the stage of accretion with $\dot{M}_{\text{Edd}} \sim 1.5 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ the white dwarf accumulated a helium envelope of $\sim 0.01 M_{\odot}$ and when the density at the bottom of the accreted layer attained $\sim 2 \times 10^5 \text{ g cm}^{-3}$ helium burning started and a thermal flash developed. We have terminated our calculations when the temperature at the bottom of the accreted envelope rose from $\sim 10^7$ to $\sim 2.7 \times 10^8$ K. Expansion of the outer layers will lead to the common envelope formation and the merger of companions. Some mass may be lost in this process.

4.2. Prompt merging scenario

It may well happen that in the real system the coalescence of white dwarfs occurs on a dynamical time scale (e.g., if the mass of the sdB star is higher than assumed, but still $t_{\text{He}} < t_{\text{GR}}$). Segretain et al. (1997) presented a three-dimensional SPH simulation of the coalescence of carbon–oxygen white dwarfs in a binary rather similar to the system expected to be formed by KPD 1930+2752: $M_1 = 0.9 M_{\odot}$ and $M_2 = 0.6 M_{\odot}$. The less massive white dwarf is disrupted on a dynamical time scale and becomes a thick disk around the more massive primary. Carbon ignition is likely to occur at the core–disk boundary, the hottest part of the merged configuration. Since this region is only weakly degenerate, carbon ignition is expected to be non-violent and nuclear burning will propagate inward, forming an ONeMg core (Nomoto & Iben 1985). Carbon continues to accrete due to viscous transport of momentum. Generation of energy by accretion is expected to transform the disk into a quasi-spherical envelope. A stationary configuration may form in which carbon burns at the same rate as it is accreted by the core (Kawai et al. 1988). During this high luminosity phase, mass loss through a stellar wind should take place. A significant part of the envelope may be lost and a massive single white dwarf will be formed.

Evolution of KPD 1930+2752 may be different in some features, important for the fate of the system. The disrupted less massive white dwarf will have a rather thick helium surface layer ($\sim 0.04 M_{\odot}$) which will be accreted by the companion first. Like in the case of carbon accretion, these external parts of the disrupted donor are heated by shocks and become the hottest part of the merger product: $T \sim (7-8) \times 10^8$ K. The time scale for the complete conversion of helium into carbon (neglecting all reactions other than the 3α -reaction) is

$$\tau_{3\alpha} \sim Y^{-3} T_8^3 \rho_6^{-2} \exp(-14.33 + 43.2/T_8) \text{ s}, \quad (2)$$

where Y is the abundance of He^4 by mass, T_8 and ρ_6 are the temperature and the density in the units of 10^8 K and 10^6 g cm^{-3} , respectively (Iben & Tutukov 1991). For $Y = 1$, $\rho \sim 10^4 - 10^5$ g cm^{-3} and $T_8 \sim 7$ one has $\tau_{3\alpha} \sim 10$ s for $\rho_6 = 0.1$ or 1000 s for $\rho_6 = 0.01$. The energy produced by the burning of $0.04 M_\odot$ of helium is $\sim 10^{50}$ erg. This energy is comparable to the binding energy of the whole envelope (former less massive dwarf). Very fast release of the energy in weakly degenerate matter may result in expansion and loss of the envelope. On the other hand, carbon burning may start and propagate inward. As a result, like in the case of *delayed* merging, one may expect the formation of an ONeMg white dwarf, but of relatively lower mass ($\lesssim 1 M_\odot$). However, these inferences, for both cases of *delayed* and *prompt* merging, have to be verified by hydrodynamic calculations.

5. Discussion and conclusion

In the absence of observed candidate double degenerate progenitors of SNe Ia, systems containing a white dwarf with a low mass helium companion and merging due to the loss of angular momentum via GWR were suggested as SNe Ia progenitors. Two routes to explosion may be envisioned.

First, the helium star may fill its Roche lobe while still burning He in the core. If He-burning isn't much advanced, the mass exchange rate upon RLOF is expected to be $\sim 3 \times 10^{-8} M_\odot \text{yr}^{-1}$ (Savonije et al. 1986; Tutukov & Fedorova 1989; Ergma & Fedorova 1990) and this may result in the so called "edge-lit" detonation after accretion of $\sim 0.1 M_\odot$ of He (Livne 1990). Another possibility is the merger of components after the helium star also becomes a white dwarf. Thus, the outcome of the evolution depends on the relation of the time scales of GWR and core helium burning. We have shown that for a system similar to KPD 1930+2752 the merger is more probable, given the state of the art input physics of our evolutionary code.

However, the situation differs from the "standard" picture of the merger of two CO white dwarfs with a dynamical disruption of the less massive dwarf, due to the presence of a helium mantle ($\sim 0.04 M_\odot$) atop the latter. If mass transfer to the more massive dwarf is initially stable, the accreted He layer may experience a thermal flash, resulting in its expansion, formation of a common envelope and the merger of two cores, accompanied by some mass loss. Another possibility is a dynamical merger, in which He will be ignited at the core-envelope interface of the merger product; about $\sim 10^{50}$ erg may be released then in 10–1000 s and expulsion of most of the material of the disrupted dwarf may be expected. In both cases it is expected that carbon will start burning in the outer layers of the core of the merger product and the flame will propagate inward, forming an ONeMg white dwarf. Thus we conclude that KPD 1930+2752 will not produce a SN Ia. Three-dimensional hydrodynamical calculations of the merging process including nuclear burning are necessary to verify these speculations.

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