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Thermonuclear outbursts of AM CVn stars

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We consider initial stage of the evolution of AM CVn type stars with white dwarf donors, which is accompanied by thermonuclear explosions in the layer of accreted He. It is shown that the accretion never results in detonation of He and accretor s in AM CVn stars finish their evolution as massive WDs. We found, for the first time, that in the outbursts the synthesis of n -rich isotopes, initiated by the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction becomes possible.

1. Introduction

AM CVn type stars are rare ($\simeq 60$ objects [1]) cataclysmic variable stars (CV) with helium white dwarf (WD) or low-mass helium star donors (see, e.g., [2]). In the present paper we consider the systems of the former kind. Evolution of AM CVn stars is governed by the loss of angular momentum due to gravitational waves radiation [3]. Immediately after formation, the rate of mass-loss by the WD donors in the AM CVn stars can reach $\sim 10^{-5} M_{\odot}/\text{yr}$; later it decreases to $\sim 10^{-11} M_{\odot}/\text{yr}$ [2]. Depending on the accretion rate onto the WD $\dot{M}_{\text{acc}}$, the burning of He in the accreted layer may be steady, occur in quasi-cyclic mild or strong thermonuclear flashes (eventually accompanied by matter ejection). Also He-detonation is possible, producing an explosive event of SN Ia proportion [4]. An extended envelope may form around the WD, if $\dot{M}_{\text{acc}}$ exceeds steady-state burning rate of He. Figure 1 shows the dependence of the burning regimes of He in the $M_{\text{WD}}\text{-}\dot{M}_{\text{acc}}$ plane according to our calculations [5]. Thermonuclear flashes accompany the earliest stage of the evolution of AM CVn stars.

We have investigated the flashes on the accreting WDs in the AM CVn type CVs with donors – helium WDs and the accompanying nucleosynthesis [6, 7]. The stars with the initial masses of components $(M_{\text{acc}} + M_{\text{don}}) = (0.6+0.17)$, $(0.92+0.15)$, $(1.02+0.20)$, and $(1.02+0.30)M_{\odot}$ were considered. Such masses are characteristic for known detached binary WDs, possible ancestors of the AM CVn stars (see discussion in [6]) and fit the model of the population of AM CVn stars [2].¹

¹Further, we will distinguish models by the initial masses of the components.

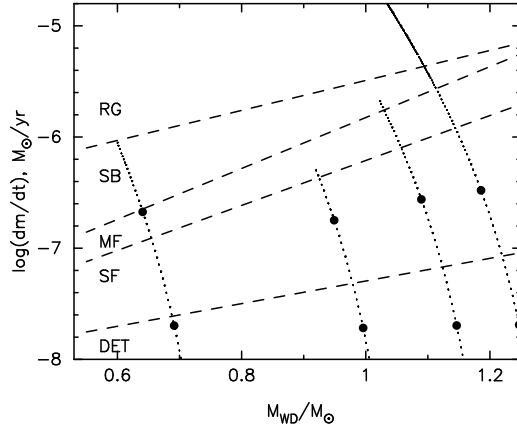


Figure 1. Helium burning regimes in the layer of accreted He depending on the mass of the accretor M_{WD} and the accretion rate $\dot{M}_{acc}$ [5]. Dashed lines mark the boundaries of the zones in which detonation (DET), strong (SF) and weak (MF) flashes, steady burning (SB) occur. In the RG-region of the diagram, extended envelopes around WDs are formed. Dotted lines show the evolutionary tracks of the stars considered in this paper. Filled circles on the tracks correspond to the age of the system 10^5 and 10^6 years.

In §2 we present the results of calculations, which are summarised in §3.

2. Results of computations

Evolution. The algorithm of computations of $\dot{M}_{don}$ is described in [2]. The evolution of accretors was calculated using 1-D FUNS evolutionary code [8]. The nuclear network included about 700 isotopes from ^1H to ^{210}Bi , coupled by $\simeq 1000$ reactions [9]. Expansion of the WDs during the flashes was limited by RLOF. It was assumed that the excess of the matter is lost from the system with the specific angular momentum of the accretor.

Accretion is accompanied by the release of gravitational energy, which “counteracts” the cooling of the WD. Heating of WD outer He-rich layer causes ignition of He. Since the matter in the burning zone is degenerate, a thermonuclear runaway occurs. Radiative transfer can not ensure the removal of released energy and there arises a convective zone propagating both inward and outward with respect to the He-ignition point. Convection removes the heat from the He-burning zone, but also mixes into it “fresh” He, stimulating burning. This process is accompanied by an

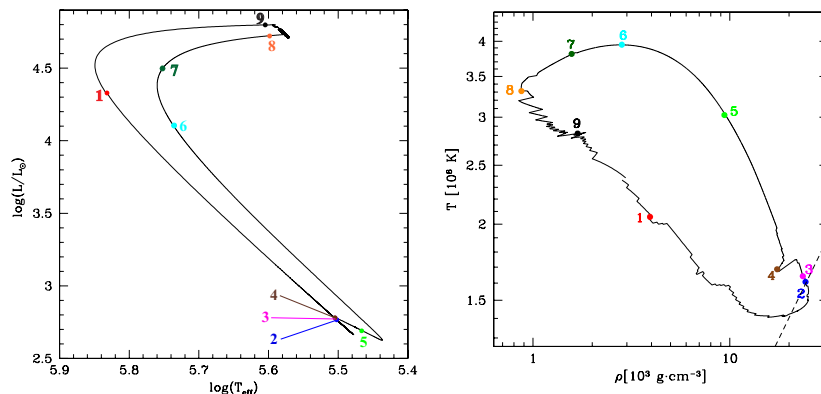


Figure 2. Left panel – evolutionary track of accreting WD in $(1.02 \pm 0.3) M_\odot$ system in the HRD. Right panel – evolution of temperature and density in the He-burning zone. 1 – resumption of accretion after previous flash, $t_{9-1}=28$ yr; 2 – He-ignition, $t_{1-2}=870$ yr; (2-3) – rapid increase of nuclear energy release, $t_{2-3}=5.93$ yr; (3-4) – thermonuclear runaway, formation of convective zone, $t_{3-4}=214$ day; 5 – maximum outward extension of convective zone, $T \approx 3 \cdot 10^8$ K, activation of $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction, onset of neutron-isotopes nucleosynthesis, $t_{4-5}=314$ day; 6 – temperature maximum in the He-burning zone ($3.8 \cdot 10^8$ K), $t_{5-6}=7.5$ day; (6-8) – active burning of ^{22}Ne , $t_{6-8}=3.57$ yr; (8-9) – RLOF stage, $t_{8-9}=8.63$ yr.

increase of the radius of the WD, which leads to the RLOF and ejection of the matter enriched by the burning products into ISM.

Evolution of the dwarf during a typical cycle triggered by a strong flash is shown in Fig. 2. Figure 3 presents the evolution of the characteristics of the burning layer for three selected models. In the system $(0.60 \pm 0.17)M_\odot$ one weak flash occurs $5 \cdot 10^4$ yr after the start of accretion and accumulation of $0.03M_\odot$ of He. After the flash, for $\simeq 2.5 \cdot 10^4$ yr the release of gravitational energy prevails over cooling, but then, because of the fall of $\dot{M}_{\text{don}}$, the temperature in the He layer starts to decrease, new flashes do not occur, and evolution ends by the formation of a CO WD with a massive He envelope. In the system $(0.92 \pm 0.15)M_\odot$, the first flash occurs 24000 yr after the start of accretion and accumulation of $0.01M_\odot$ of He. The flash turns out to be “strong”, because $\dot{M}_{\text{acc}}$ is low (Fig. 1) and the degeneracy of matter at the base of He layer by the time of the flash is higher than in the other considered systems. Afterward, 4 more flashes occur. The time interval between flashes and their power are increasing,

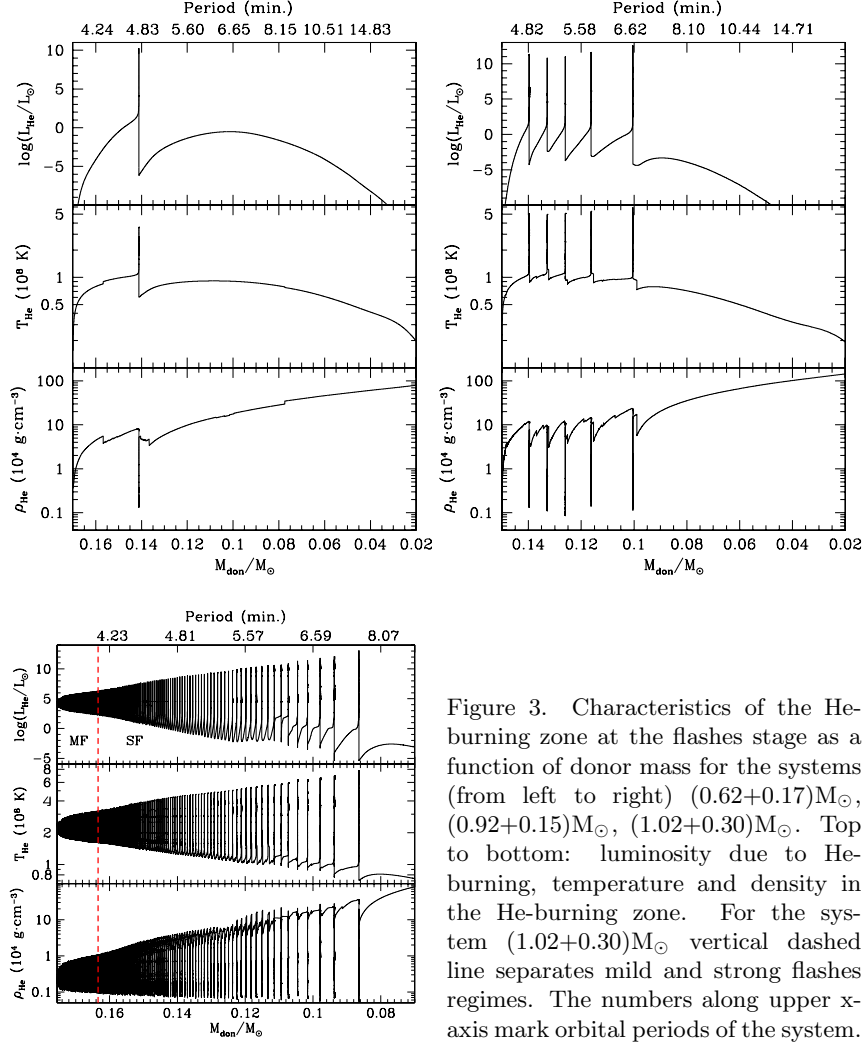


Figure 3. Characteristics of the He-burning zone at the flashes stage as a function of donor mass for the systems (from left to right) $(0.62+0.17)M_{\odot}$, $(0.92+0.15)M_{\odot}$, $(1.02+0.30)M_{\odot}$. Top to bottom: luminosity due to He-burning, temperature and density in the He-burning zone. For the system $(1.02+0.30)M_{\odot}$ vertical dashed line separates mild and strong flashes regimes. The numbers along upper x-axis mark orbital periods of the system.

because of the decline of $\dot{M}_{\text{acc}}$. Evolution ends, like in the case of the system $(0.60+0.17)M_{\odot}$, by transformation of the accretor into a massive CO WD with a thick He-mantle. In the system $(1.02 + 0.30)M_{\odot}$, immediately after the contact $\dot{M}_{\text{acc}}$ exceeds the rate of stationary He-burning, but the matter excess is only $\simeq 0.01M_{\odot}$ and the common envelope which can be formed hardly influences the evolution of the system. Progressively

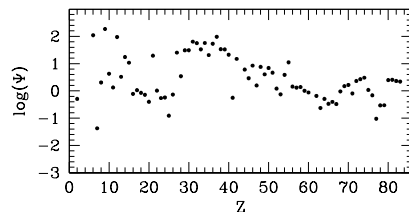


Figure 4. The factor of elemental enrichment for the matter lost by the system $(1.02+0.3)M_{\odot}$ in strong flashes.

stronger flashes begin 120 yr after contact. Altogether, 50 mild and 87 flashes occur. Matter retention efficiency in flashes gradually decreases from 1 to 0. After the 87th strong flash, $M_{\text{acc}} \approx 1.1M_{\odot}$, $M_{\text{don}} \approx 0.07M_{\odot}$. Further accretion does not lead to flashes, a massive WD forms, like in the other cases.

Nucleosynthesis. During strong flashes the physical conditions are suitable for the activation of the *intermediate neutron capture process* (“*i-process*”), which occurs when the number density of neutrons is $n_n \approx (10^{14} - 10^{16}) \text{ cm}^{-3}$ [10]. Until recently, *i*-process was associated with the late AGB or post-AGB stars, still hypothetical “rapidly accreting WDs”. As a source of neutrons, the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction was considered, which occurs when protons are ingested during a He-flash by convection into the hot He- and C-rich zone, resulting in the appearance of regions with high concentrations of neutrons. Since in the AM CVn stars WD accretes the matter that does not contain hydrogen, ^{13}C is not synthesised. But as it is shown in Fig. 3, already at the stage of mild flashes the temperature in the He-burning zone attains $3 \cdot 10^8 \text{ K}$ and in the case of strong flashes $- 10^9 \text{ K}$. Under such conditions, the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction is activated, which becomes the source of neutrons for the *i*-process, resulting in the formation of isotopes up to the stable ^{208}Pb .

During the flashes, WD loses all (or a part of) the layers with modified chemical composition. The latter can be characterized by the factor of elemental enrichment $\Psi = N_{\text{el}}/N_{\text{ISM}}$, where N_{el} and N_{ISM} are relative concentrations of a certain element in the matter lost by the star and the ISM, respectively. As an illustration, Fig. 4 shows the value of Ψ for the matter lost by the system $(1.02+0.30)M_{\odot}$ during strong flashes. In total, the system lost $0.051M_{\odot}$ of the matter with chemical composition of accretor and $0.052M_{\odot}$ of the matter enriched in α -elements and neutron-rich isotopes.

3. Conclusion

AM CVn stars with WD donors experience less than 100 flashes per system in the first $\sim 10^5$ yr of existence. Formation rate of such AM CVn

stars is $\sim 10^{-3}$ per year [2]. The flashes occur predominantly on the most massive WDs, therefore, we can roughly estimate that currently in the Galaxy may exist ~ 10 AM CVn stars experiencing thermonuclear flashes.

Even the most massive of the systems studied by us do not experience the “last”, dynamic flash that destroys accretor. Therefore, at least within the framework of our assumptions, the hypothetical optical transients SN Ia [11] do not exist.

We found that the nuclear i -process triggered by the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction, which is usually associated with massive stars, can occur during the outbursts of He burning on accreting WDs. However, rare AM CVn stars are vanishingly unimportant for the chemical evolution of the Galaxy. But their phenomenon shows that some exotic nuclear processes can occur in the depths of stars, hidden to the observers.

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