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Letter to the Editor

He-detonation in sub-Chandrasekhar CO white dwarfs: A new insight into energetics and p-process nucleosynthesis

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Abstract. He-accreting white dwarfs with sub-Chandrasekhar mass are revisited. The impact of the use of an extended reaction network on the predicted energy production and characteristics of the detonating layers is studied. It is shown that the considered scenario can be the site of an αp-process combined with a p-process and with a variant of the rp-process we refer to as the pn-process. We define the conditions under which the derived distribution of the abundances of the p-nuclides in the ejecta, including the puzzling light Mo and Ru isotopes, mimics the solar-system one.

Key words. hydrodynamics – nuclear reactions – nucleosynthesis – shock waves – stars: white dwarfs

1. Introduction

The outcome of He-accreting sub-Chandrasekhar white dwarfs (WD) has deserved a special attention since the early 80's (e.g. Nomoto 1982; Woosley et al. 1986). Iben & Tutukov (1991) have investigated the evolution of a close binary system leading to the formation of a compact CO WD accreting He from a nondegenerate low-mass companion. Limongi & Tornambe (1991) concluded that such systems could in some conditions lead to explosive phenomena. Their relatively high estimated frequency, around 0.01 y^{-1} (Iben & Tutukov 1991), have drawn attention to their possible connection with the progenitors of type Ia supernovae.

He-accreting CO WDs are not viewed today as the most likely candidates for such explosions (e.g. Höflich & Khokhlov 1996; Hillebrandt & Niemeyer 2000; Branch 2001), but they might well be responsible for some special types of events. In fact, some one-dimensional calculations (e.g. Woosley & Weaver 1994 and references therein) have concluded that He-detonations on the considered WDs could well be identified as peculiar supernovae, characterized by rapidly declining light curves with lower maximum luminosities than those reached by C-deflagration Chandrasekhar-mass WDs. These properties are reminiscent of subluminous supernovae like SN 1991bg. Multidimensional simulations have confirmed the onset of the He-detonation, but have revealed significant differences in the central C-ignition which may be triggered by the He-detonation (Livne & Arnett 1995; Garcia-Senz et al. 1999).

This Letter limits its focus to some aspects of the surface He detonation which have not deserved much attention up to now. More precisely, we want to test the classical practice of calculating the energy production and associated nucleosynthesis through a nuclear reaction network made of (α, γ) captures. This approach is obviously unable to treat the production or captures of protons and neutrons in the detonating layers as well as their impact on the energetics and the nucleosynthesis of the He detonation. Concomitantly, we present the first detailed calculation of the synthesis of the nuclides heavier than the iron peak in the considered He detonation. These problems are tackled in the framework of a 1-D model of the He detonation, the details of which are presented in Sect. 2. Section 3 discusses the impact of the use of an extended reaction network on the predicted energy production and characteristics of the detonating layers. The composition of the ejected material is analyzed in Sect. 4. We demonstrate that the considered scenario can be the site of an αp-process combined with a p-process and with a variant

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of the *rp*-process we refer to as the *pn*-process. We define the conditions under which the derived distribution of the abundances of the *p*-nuclides mimics the solar-system one. Conclusions are drawn in Sect. 5.

2. The He-detonation model

We consider a non-rotating 0.8 $M_\odot$ CO-WD made of 30% C and 70% O by mass (Salaris et al. 1997). It is stabilized and cooled to an initial luminosity $L_{\rm wd} = 0.01\ L_\odot$, the central density and temperature being $\rho_{\rm c} = 1.13 \times 10^7$ g cm^{-3}, and $T_{\rm c} = 1.14 \times 10^7$ K. The accreted matter is He-rich ($X(^4{\rm He}) = 0.98$), and is assumed to contain traces of other nuclides: $X(^{12}{\rm C}) = 5 \times 10^{-3}$, $X(^{16}{\rm O}) = 5 \times 10^{-3}$ and $X(^{14}{\rm N}) = 10^{-2}$ [$X(i)$ is the mass fraction of nuclide i]. As pointed out by Woosley & Weaver (1994), the consideration of an initial non-zero ^{14}N amount is critical. The ^{14}N mass fraction adopted here results from the burning of H in the companion assumed to be of typical Pop I composition, but its precise value is considered by Woosley & Weaver (1994) not to be critical for the He detonation outcome. The accretion rate on the CO-WD is adopted equal to $3.5 \times 10^{-8}\ M_\odot$ y^{-1}, in agreement with the values reported by Limongi & Tornambè (1991). The classical assumption is also made that the accreted material has the same specific entropy as the outermost WD shells. In these conditions, a thick He-rich envelope forms on the WD surface.

The evolution of this envelope is followed with a modified version of the code SHIVA described by José & Hernanz (1998). It is a spherically symmetric, implicit, hydrodynamic code in Lagrangian formulation which has been used extensively for the modeling of classical nova outbursts. For the simulation reported here, a fine Lagrangian mass grid of 400 shells is adopted. Shell masses range from $10^{-7}\ M_\odot$ for the innermost shells to $10^{-4}\ M_\odot$ for the outer layers. The adopted nuclear reaction network is discussed in Sect. 3.

A thermonuclear runaway develops near the base of the He envelope when about 0.18 $M_\odot$ has been accreted. At this point, the density reaches a critical value of about 10^6g cm^{-3} allowing the transformation $^{14}{\rm N}({\rm e}^-,\nu)^{14}{\rm C}$. When the temperature gets high enough, the resulting ^{14}C transforms into ^{18}O through $^{14}{\rm C}(\alpha,\gamma)^{18}{\rm O}$, this α-particle consumption channel competing successfully with the 3α-reaction in the relevant temperature and density regimes (Hashimoto et al. 1986; also Piersanti et al. 2001). The associated energy release triggers the detonation of He. More precisely, two shock waves propagate inward and outward from the He-ignition shell. The outward-moving He-detonation wave heats the matter to temperatures around 3×10^9 K. The expansion velocities range from 1000 km s^{-1} in the vicinity of the He-ignition shell to more than 20 000 km s^{-1} when the front reaches the WD surface, which is achieved in only 0.176 s. The whole envelope is ejected into the interstellar medium.

The ingoing compressional wave pushes the inner WD material to velocities of nearly ∼3000 km s^{-1}. Its temperature, however does not exceed 5×10^8 K, which does not allow to trigger the burning of carbon. The WD centre is reached by the compressional wave after 0.7 s. As a result, carbon ignites, and a second detonation develops near the centre. The high temperatures encountered during the C-deflagration ($T_9 \gtrsim 4$), as well as the initial composition of the CO WD lead mainly to the production of iron-peak nuclei and are not expected to affect the nucleosynthesis of the *p*-nuclei. For this reason, the calculations do not follow the evolution of the inner part after C-ignition, so that only the fate of the He-detonating envelope is modeled here.

3. The energetics of the He detonation

The estimate of the energy released by the He detonation is generally derived from the use of a limited network of some 50 nuclear reactions and 26 nuclides. In addition to the (α,γ)-chains from He to Ni, it is made of the $^{14}{\rm N}({\rm e}^-,\nu)^{14}{\rm C}(\alpha,\gamma)^{18}{\rm O}$ and the C+C, C+O and O+O reactions. Reverse photodisintegrations are also included. Post-processing calculations based on a full network to be described in Sect. 4 demonstrate that the detonation produces substantial amounts of neutrons and protons through $(\alpha,{\rm n})$ and $(\alpha,{\rm p})$ reactions. They induce nucleon capture reactions that modify substantially the nuclear flow predicted by the limited network, and concomitantly the energetics of the detonation and the associated nucleosynthesis. For these reasons, an extended nuclear reaction network inspired by the post-processing calculations has been implemented in the hydrodynamic simulations. It includes 188 nuclides up to ^{68}Zn linked through a net of 571 nuclear reactions. These reactions are selected on grounds of the fact that they contribute to more than one per mil of the total energy generated at any timestep. They comprise neutron, proton and α-captures, as well as photodisintegrations and β-decays. Although the new calculations are extremely time consuming, they are considered to be essential for a reliable determination of the energetics of the He detonation and of the thermodynamics of the He shells. In fact, the pre-explosion evolution at $T < 10^8$ K is not affected by the network extension. Differences are found at temperatures in excess of 10^9 K, where a large number of reactions neglected in the reduced networks are responsible for an increase of the energy deposited in the envelope. In our simulations, the reduced network leads to a peak temperature of the He-burning shell of 3.38×10^9 K, with a maximum rate of energy production of $Q_{\rm nuc} = 2.2 \times 10^{21}$ erg/g/s, while a peak temperature of 3.83×10^9 K and $Q_{\rm nuc} = 4.5 \times 10^{22}$ erg/g/s are obtained with the extended network. The He-detonation wave hits the WD surface a bit earlier (0.166 s) than with the reduced network (0.176 s). As an example, we display in Fig. 1 the quite significant differences in the evolution of T and $Q_{\rm nuc}$ predicted with the two networks for a layer located about $5 \times 10^{-3}\ M_\odot$ above the base of the He-burning shell. In fact, the considered layer is seen to experience a unique energy burst due to the α-chain of the

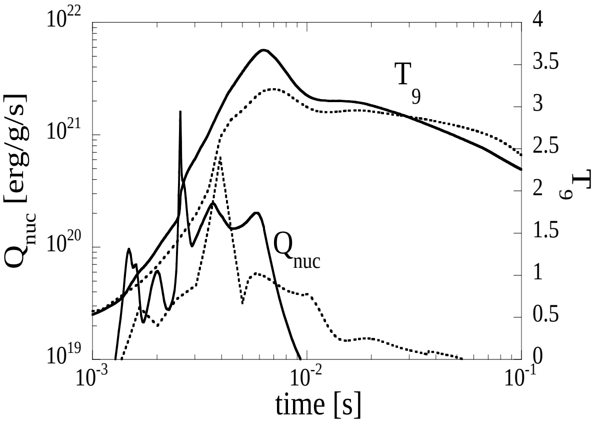

Fig. 1. Comparison of the evolution of the rate of nuclear energy production and of temperature predicted with the reduced (dashed lines) and with the extended network (solid lines) in a layer located about 5×10^{-3} $M_\odot$ above the base of the burning shell.

reduced network (involving solely $N = Z$ nuclei), and in particular to ^{20}Ne$(\alpha,\gamma)^{24}$Mg$(\alpha,\gamma)^{28}$Si. The extended network leads to an initial double energy burst, the first one being due to ^{14}C$(\alpha,\gamma)^{18}$O, the second one resulting from radiative neutron captures on the most abundant species. The reactions ^{18}O$(\alpha$, n$)^{21}$Ne, followed by ^{22}Ne$(\alpha$, n$)^{25}$Mg and ^{26}Mg$(\alpha$, n$)^{29}$Si are indeed responsible for a neutron density as high as $N_{\rm n} \simeq 10^{22}$ cm^{-3}. At later times, the major energy burst results from the main α-chain burning. It develops earlier than the peak obtained with the reduced network, this time shift being due to the faster temperature increase predicted with the extended network. It is followed by a secondary $Q_{\rm nuc}$ peak resulting from the capture of protons produced by $(\alpha$, p) reactions on $Z \simeq N$ nuclei, and in particular on ^{44}Ti, the mass fraction of which reaches about 5×10^{-3}. At the peak temperature of $T_9 \simeq 3.6$ reached in this layer, the proton mass fraction amounts to $X_{\rm p} \sim 6\times10^{-3}$.

4. The nucleosynthesis in the He detonation

The composition of the 0.18 $M_\odot$ of ejected envelope is evaluated by a post-processing nucleosynthesis calculation based on the temperature and density profiles derived from the extended-network simulation described in Sect. 3. A full network including some 50 000 reactions on about 4000 nuclides up to Po and lying between the proton and neutron drip lines is solved for each of the 100 envelope layers. All experimental and theoretical reaction and β-decay rates are taken from the Nuclear Network Generator of the Brussels Library (Jorissen & Goriely 2001). This network is also the one used to define the minimum network that had to be implemented in the hydrodynamic simulations to calculate the nuclear energy production in each layer of the model (Sect. 3). The initial envelope composition is described in Sect. 2 for the light nuclei and assumed to be solar above Ne.

As already explained in Sect. 3, the pattern of nuclear reactions developing during the explosion is rather complex. Initially, a high neutron irradiation (neutron densities $N_{\rm n} \simeq 10^{22}$–10^{23} cm^{-3}) originating from ^{18}O$(\alpha$, n$)^{21}$Ne, and later from ^{22}Ne$(\alpha$, n$)^{25}$Mg and ^{26}Mg$(\alpha$, n$)^{29}$Si, drives most of the flow to the neutron-rich side of the nuclear chart. A weak r-process ensues. However, the increase of temperature above $T_9 \gtrsim 1.5$ induces fast photodisintegrations driving the matter back to the valley of β-stability, and even to its neutron-deficient side. From this point on, two major nucleosynthesis processes take place.

In the layers with peak temperatures $2 \lesssim T_9 \lesssim 3$, a typical p-process is found reponsible for the production of the stable p-nuclides (Rayet et al. 1995). In these conditions, the nuclear flow is dominated by $(\gamma$, n), $(\gamma,{\rm p})$ or (γ,α) photodisintegrations, complemented with mainly some neutron captures. For layers with peak temperatures $T_9 \gtrsim 3$, large amounts of ^{40}Ca and ^{44}Ti are produced by radiative α-captures. Further α-captures proceed through $(\alpha$, p) reactions, so that a so-called αp-process develops, the resulting proton mass fraction reaches about $X_{\rm p} = 6\times10^{-3}$. In the considered hot environment, these protons are rapidly captured to produce heavier and heavier neutron-deficient species, making up a kind of "proton-poor rp-process", in view of the much lower proton concentrations than in the "classical" rp-process. In this process, some nuclei are produced with proton separation energies that are small enough to experience $(\gamma$, p) photodisintegrations which slow down the nuclear flow. However, (n, p) reactions made possible by the high neutron density (at this stage, $N_{\rm n} \simeq 10^{19}$ cm^{-3}) revive the flow towards higher-mass nuclei by new p-captures. One might thus talk about a "proton-poor neutron-boosted rp-process", which we coin the pn-process. The nuclear flow associated with this variant of the rp-process lies much further away from the proton-drip line than in the classical rp-process. This results from the lower proton and non-zero neutron concentrations encountered in the He detonation. A detailed discussion of this pn-process nuclear flow and of the associated nuclear physics uncertainties will be presented elsewhere.

The final envelope composition is displayed in Fig. 2a. As a new nucleosynthesis prediction associated with the He detonation, we note that almost all the p-nuclei are overproduced in solar proportions within a factor of 3 as a combined result of the p- and pn-processes. This includes the puzzling Mo and Ru p-isotopes (Rayet et al. 1995; Costa et al. 2000) which are efficiently produced at peak temperatures $T_9 \gtrsim 3.5$. The lighter Se, Kr and Sr p-isotopes are synthesized in layers heated to $3 \lesssim T_9 \lesssim 3.5$, ^{78}Kr being the most abundantly produced in these conditions. The high sensitivity to temperature of the production of the $A < 100$ p-nuclei makes the correct description of the corresponding layers (and thus the use of a suitably extended reaction network) mandatory.

Figure 2a also makes evident that the Ca-to-Fe nuclei are overabundant with respect to the p-nuclei but

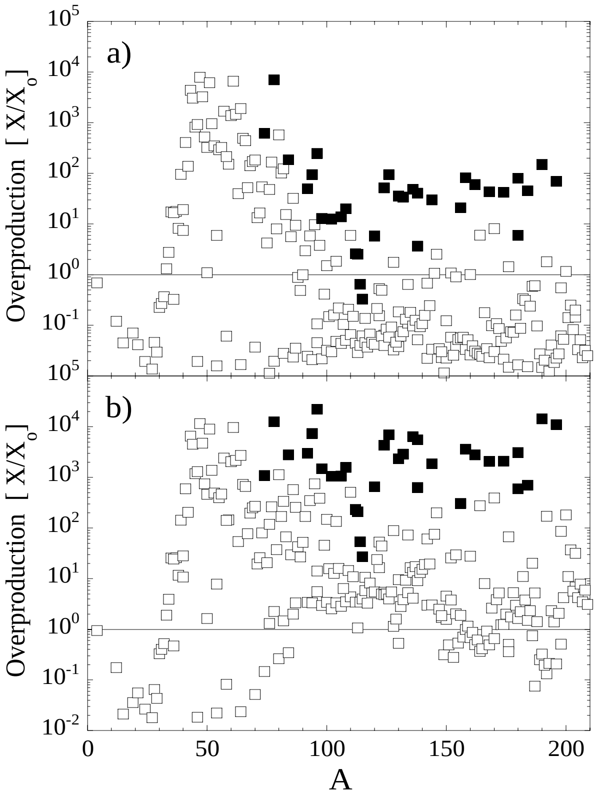

Fig. 2. a) Final composition of the ejected envelope as a function of the mass number A. Full symbols denote the p-nuclides. **b)** Same as **a)**, but the initial abundances of the s-nuclides is assumed to be 100 times solar.

^{78}Kr by a factor of about 100, which implies that the considered He detonation is not an efficient scenario for the production of the bulk solar-system p-nuclides. In order to cure this problem, one may envision enhancing the initial abundance of the s-nuclides, which are the seeds for the p-process. Figure 2b shows that an increase by a factor 100 of the s-nuclide abundances over their solar values makes the overproduction of a substantial variety of p-nuclides comparable to the one of ^{78}Kr and of the Ca-to-Fe nuclei. The factor 100 enhancement would have to be increased somewhat if the material processed in the core of the CO-WD by C-detonation were ejected along with the envelope. At this point, one essential question concerns the plausibility of the required s-nuclide enhancement. We do not have any definite answer to this key question. The required s-process enrichment of the accreting WD might result from its past AGB history if indeed some of its outer s-process enriched layers could be mixed convectively (or due to rotationnal effects) with part at least of the accreted He-rich layers before the detonation. Alternatively, the He-rich matter accreted by the CO-WD could be (or become) enriched in s-process elements. Such speculations (e.g. Iben & Tutukov 1991) need to be confirmed by detailed simulations.

5. Conclusion

This Letter presents the first instance of a clear possibility for αp processed material to be ejected into the interstellar medium. In previously proposed sites, like accreting neutron stars associated to X-ray bursts or accretion disks around black holes (e.g. Schatz et al. 1998), such an ejection is indeed far from being demonstrated. Of course, the global contribution of He-detonating CO-WD to the galactic nuclidic content remains uncertain, but there is reasonable hope for it not to be negligible in view of the predicted frequency of about 0.01 per year for these events. We also find that this galactically "fertile" αp process is accompanied with an efficient p-process and triggers a variant of the rp-process, the pn-process, which develops in the presence of neutrons and with less protons than the classical rp-process. Most of the p-nuclides, including the puzzling light Mo and Ru isotopes, are found to be co-produced in these conditions in relative quantities close to solar. Unfortunately, they are underproduced (except ^{78}Kr) with respect to the Ca-to-Fe species. The price to pay in order to avoid this difficulty is an increase of the abundances of the seed s-nuclei by a factor of about 100 over their solar values. The astrophysical plausibility of this enhancement remains to be scrutinized in detail, in particular by studying the impact of rotationally induced mixing.

In spite of this problem, we consider that the results presented here are encouraging enough for justifying an extension of our calculations to other situations involving CO-WD of different masses and accretion rates. These additional simulations will be presented elsewhere, along with a detailed discussion of the characteristics and nuclear physics uncertainties of the associated αp, pn- and p-process flows.

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