Helium stars as supernova progenitors

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Abstract. We follow the evolution of helium stars of initial mass \((2.2 - 2.5) M_\odot\), and show that they undergo off-center carbon burning, which leaves behind \(\sim 0.01 M_\odot\) of unburnt carbon in the inner part of the core. When the carbon-oxygen core grows to Chandrasekhar mass, the amount of left-over carbon is sufficient to ignite thermonuclear runaway. At the moment of explosion, the star will possess an envelope of several \(0.1 M_\odot\), consisting of He, C, and possibly some H, perhaps producing a kind of peculiar SN. Based on the results of Waldman & Barkat (2007) for accreting white dwarfs, we expect to get thermonuclear runaway at a broad range of \(\rho_c \approx (1 - 6) \times 10^9 \text{g cm}^{-3}\), depending on the amount of residual carbon. We verified the feasibility of this scenario by showing that in a close binary system with initial masses \((8.5 + 7.7) M_\odot\) and initial period of 150 day the primary produces a helium remnant of \(2.3 M_\odot\) that evolves further like the model we considered.

1. Introduction

Type Ia supernovae (SN Ia) have a relatively small dispersion of luminosity (the standard deviation in peak blue luminosity is \(\sigma_B \approx 0.4 - 0.5\) mag., Branch & Miller (1993)) and are being used as distance indicators (“standard candles”), having especial significance in the effort of determining the cosmological parameters of our universe.

The long-standing explanation of the SN Ia phenomenon has been the explosive burning of degenerate carbon in the core of a carbon-oxygen white dwarf, which becomes unstable as it grows to Chandrasekhar mass \(M_{Ch}\) either by accretion from a binary companion or by a merger of two white dwarfs, following the angular momentum loss from the system by gravitational wave radiation. However, theoretical models are still far from self-consistently producing an evolutionary path towards the progenitor and reproducing crucial features of the observational data, such as the composition of the ejecta. For a detailed review of the above see, e.g., Leibundgut (2000); Hillebrandt & Niemeyer (2000); Filippenko (2005).

As well, SN Ia can not be regarded as perfectly homogeneous class, since their Hubble diagram exhibits scatter larger than the photometric errors, while spectroscopic and photometric peculiarities have been noted with increasing frequency in well-observed SN Ia (e.g., Filippenko 2005).

Therefore, there is an obvious need for progenitor scenarios that could explain the diversity among SN Ia. Several explanations have been suggested, such

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as variations in the metallicity of the progenitor, in the carbon to oxygen ratio at its center, or in the central density at the time of ignition (e.g., Timmes et al. 2003; Röpke et al. 2006; Lesaffre et al. 2006). The variation of the latter two parameters is expected to result from the variation in the initial white dwarf mass and in the accretion history.

In this work we follow the evolution of helium stars with initial mass \( \approx (2.2 - 2.5) M_\odot \) and show that they might reach thermonuclear explosion and perhaps account for some of the peculiar SNe.

2. Results

We followed in detail the evolution of a 2.4\( M_\odot \) helium star, starting from a homogeneous object. We used the TYCHO evolutionary code described in Young & Arnett (2005). The helium burning convective core has an almost constant mass of about 0.82\( M_\odot \), and produces a CO core with \( X_C \approx 0.27 \). Subsequently, a radiative helium burning shell develops above the core, and as the core grows to about 1.1\( M_\odot \) carbon is ignited in the core at about 0.3\( M_\odot \) (Fig. 1, left panel). After the end of core helium burning the center of the star becomes increasingly degenerate, and neutrino cooling is increasingly competing with contraction-induced heating. As a result, the maximum temperature is attained at an off-center point and it keeps growing until carbon ignites there (Fig. 1, right panel). Following off-center C-ignition, the center expands and cools, and a series of carbon burning flashes occurs. Eventually burning ceases when carbon is almost exhausted in the core, however as can be seen in Fig. 2, the innermost 0.5\( M_\odot \) of the core has a residual \( X_C \approx 0.02 \).

After carbon burning ceases, the center continues to heat and contract while the helium burning shell gradually increases the mass of the core. Similarly to AGB evolution, the luminosity of the star grows, causing the envelope to expand and to develop a deepening convective region, which at certain moment penetrates into the helium burning shell and creates conditions for hot bottom burning. During this stage the carbon that accumulates below the helium burning shell quasi-periodically ignites (see Fig. 1, left panel), similarly to the helium flashes occurring in AGB stars. Since very little is known about the mass loss rate of stars of the kind we consider, we applied Reimers (1975)-based rate, which reduced the mass of the star to \( \approx 1.8\ M_\odot \) (Fig. 1, left panel).

Finally, the core grows to \( M_{Ch} \) due to the helium burning shell and carbon in the center ignites (Fig. 1, right panel). Convection is initiated, supplying more carbon to the central region, and if the amount of carbon is sufficient to raise the temperature above the oxygen ignition threshold (\( \approx 1.5 \times 10^9 \) K), which indeed happens in this case, oxygen will ignite under degenerate conditions and initiate an explosion similar to the classical SN Ia case.

Models with initial masses (2.2 - 2.5)\( M_\odot \) evolve very similarly to the 2.4\( M_\odot \) case, developing a carbon residue which might ignite thermonuclear runaway. We did not follow the evolution further through the hot-bottom burning stage. The 2.1\( M_\odot \) model only ignites carbon at a later stage, below the helium burning shell, similar to the carbon flashes encountered in the 2.4\( M_\odot \) case, however, since in this case carbon has not been previously depleted in the core, burning will probably continue until it reaches the center. We have not followed this
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Figure 1. Evolution of the initially $2.4 M_\odot$ helium star model. Left: Kippenhahn plot after the end of core helium burning. Light (red) filled areas are convective, dark (blue) line shows maximum thermonuclear energy production rate. Right: Evolution of stellar center on temperature vs. density plane (long dash (green) line); also shown is the $\rho - T$ relation of the inner part of the model prior (short dashed (dark blue) and dotted (purple) lines) and immediately after off-center carbon ignition (dot-dashed (light blue) line). Carbon ignition line for $X_C = 0.25$ is shown as solid (red) line.

Figure 2. Composition of the initially $2.4 M_\odot$ helium star model before thermonuclear runaway.

model further. The models of $2.6 M_\odot$ and more massive ones ignite carbon very close to or at the center, so that the carbon residue is either non-existant or insufficient for thermonuclear runaway.
In an earlier work [Waldman & Barkat 2007] we explored the similar case of CO white dwarfs undergoing off-center carbon burning followed by mass accretion. As a function of the amount of residual carbon we got thermonuclear runaway at a broad range of $\rho_c \approx (1 - 6) \times 10^9$ g cm$^{-3}$. Since the structure of the CO core in our helium star models is very similar to that of the mass accreting CO white dwarfs, we expect to get a similar result at runaway.

Supernova which results from thermonuclear runaway in the remnant of He-star most probably will not differ photometrically from a “normal” SN Ia, but one may expect presence of strong He-lines in the spectrum, thanks to thick He-mantle of pre-SN, making this SN Ia “peculiar” (N. Chugai, priv. comm.).

To complete the picture, we tested whether a hydrogen-deficient star very similar to our initial models could be created as a result of close binary evolution. We begun with a binary of $(8.5 + 7.7) M_\odot$, with an orbital period of 150 day. After the stage of Roche lobe overflow, the primary has a total mass of $2.3 M_\odot$, a CO core of $1.2 M_\odot$, and a surface hydrogen mass fraction of 0.14. Later, wind mass loss and sporadic RLOF reduce the mass to $2.1 M_\odot$. Further evolution of the remnant is similar to the above described.

To summarize, we showed that evolution of helium stars with initial mass about $(2.2 - 2.5) M_\odot$, which might be produced in close binaries, may suggest a SN scenario in which thermonuclear runaway in $M_{Ch}$-mass cores is initiated by a very small amount of residual carbon, while the stars still have a several $0.1 M_\odot$ envelope consisting mostly of helium, carbon and possibly some hydrogen. In order to give a well justified statement on the observational outcome, our pre-SN models should be used for detailed simulations of the explosive runaway and spectra modeling.

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