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A new route to massive helium-rich hot subdwarfs

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Abstract. Hot subdwarf (SD) stars provide a valuable opportunity to study stellar evolution, binary evolution, and element diffusion. In the conventional binary evolution scenario, SDs are believed to be the stripped cores of red giants. Here, we propose a new formation process for massive hot subdwarfs called the asymptotic giant branch (AGB) common envelope (CE) channel, which involves a CE ejection with an AGB star. This alternative pathway can explain helium-rich SDs with $\log(n_{\rm He}/n_{\rm H}) > -1$ due to the partial hydrogen burning in the envelope.

Key words: hot subdwarfs – asymptotic giant branch

1. Introduction

Hot subdwarfs (SDs), located in the region of extremely horizontal branch on the HR diagram, represent an intermediate phase between the red giant branch (RGB) and white dwarf (WD) cooling sequence (Heber, 2016). The structure of SDs is relatively simple, consisting of a helium (He)-burning core and a thin hydrogen (H)-rich envelope. To achieve this structure, it is crucial to remove the H envelope when the star ascends to the RGB. However, it is insufficient to unbind this envelope for a RGB star by the internal mechanisms only. Binary interactions have been identified as an efficient way for stripping off the H-rich envelope from SD progenitors (e.g. Han et al., 2002).

There are three main channels through which SDs can form: (1) stable Roche lobe overflow channel: As the primary star (SD progenitor) fills its Roche lobe, the envelope is stripped in a stable manner; SD binaries produced from this channel typically have orbital periods ranging from hundreds to thousands of days;

(2) common envelope (CE) ejection channel: binary would enter into CE phase when binary mass transfer proceeds in a dynamically unstable way; successful ejection results in the formation of an SD; these binaries tend to have close orbits and various types of companion stars such as planets, brown dwarfs, main sequence stars, or WDs; (3) Merger channel: SDs are formed through the merger of two He WDs. These three pathways collectively offer reasonable explanations for the general characteristics observed in most SDs. However, theoretical models encounter difficulties when it comes to explaining certain peculiar properties exhibited by some SDs, such as their surface element abundance distribution.

The chemical peculiarity found on the surface of SDs is particularly intriguing, especially with regards to He abundance. Consequently, studying the distribution of surface abundances in SDs can provide valuable insights into their formation and evolution processes. Previous researches have shown that the distribution of He abundances spans a wide range ($-4 < \log(n_{\rm He}/n_{\rm H}) < 3$). Currently, there is no single unified theory that can account for this diversity in He abundance among SDs. In other words, the diversity of He abundance may suggest different formation pathways for SDs.

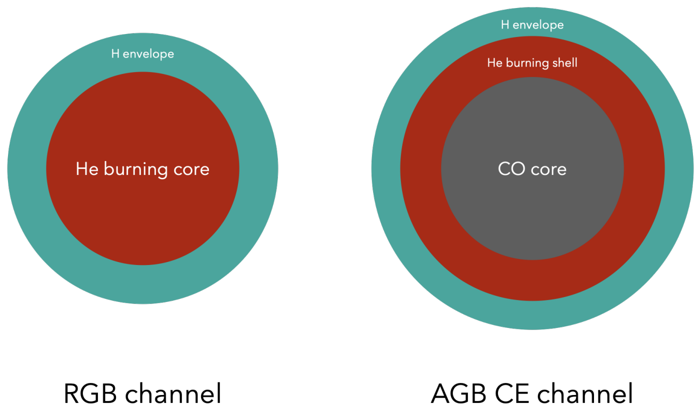

Figure 1. Initial SD structures for SDs from different channels. The cartoons are drawing not to scale.

Here we propose a novel mechanism involving an asymptotic giant branch (AGB) star undergoing CE ejection as one possible route leading to a specific type of SD. Unlike RGB stars where only H burning occurs in their cores, AGB stars have already burned their He cores into carbon-oxygen (CO) cores. As a result, an SD produced through the AGB CE channel would possess a large CO core along with surrounding H/He-burning shells and an outer H envelope, as shown in Figure 1. We found that such structure naturally explain some special SDs in the observations.

2. Methods

The simulations are conducted using the stellar evolution code Modules for Experiments in Stellar Astrophysics (MESA, version 12115; Paxton et al., 2015). We examine two scenarios of metallicity: $Z = 0.02$ and $Z = 0.001$. Additional important inputs are described by Li et al. (2024). The process of CE currently cannot be simulated by MESA. In this study, we approximate the CE process by assuming a high rate of mass loss ($> 10^{-3} M_{\odot}/\mathrm{yr}^{-1}$). Initially, we evolve a single star until it reaches the early-AGB, where the CE occurs. Then, we artificially remove the envelope with a high rate of mass loss until the H envelope mass drops below a predetermined value. We do not consider the case of stripping stars from thermal-pulse AGB because the complex physical processes of the thermal-pulse phase may lead to numerical difficulties when high mass-loss rates are assumed. In our simulations, the remaining H envelope mass is less than $0.01 M_{\odot}$, therefore, the stripping star would avoid the AGB phase since the H-envelope is too thin to ignite H shell burning.

Figure 2 shows an example illustrating how SDs can be formed through AGB CE channel. We start with an initial stellar mass of $3.0 M_{\odot}$ and metallicity $Z = 0.02$. The star evolves into early AGB phase before undergoing CE at the position indicated by the black open circle. Subsequently, we remove most of its envelope through a high mass-loss rate until only $0.01 M_{\odot}$ remains. This results in an SD with a total mass of $0.55 M_{\odot}$, initially containing a CO core of $0.33 M_{\odot}$. The thick line represents $\log L_{\mathrm{He}} > 0$, where $\log L_{\mathrm{He}}$ represents He-burning luminosity. After the end of He and H burning in the envelope, the SD ultimately transforms into a CO WD.

An interesting point is that the AGB CE scenario is quite similar to the so-called "born-again AGB stars" (Iben, 1984; Miller Bertolami, 2024). The born again scenario occurs at the late thermal pulse after the AGB stage, where most of the H envelope has already been lost through strong AGB winds. The He burning in the shell drives the thermal pulse and pushes the star back into giant branch. The biggest difference between these two models is the helium shell mass remained. In the AGB CE channel, the stripping processes occur at the early-AGB stage, resulting in SDs that still retain a significant part of He in the envelope. However, in the born again scenario, the majority of helium in the core has been fused into C/O, leaving typically less than $10^{-2} M_{\odot}$ of residual He (Miller Bertolami, 2024). Then the evolutionary timescales of the stars from AGB CE channel (from several 10^4 to several 10^6 yr) are longer than those of born again scenario ($\sim 10^4$ yr).

3. Results

We first compare our results with the observational data on $\log T_{\mathrm{eff}} - \log g$ plane. The three solid lines shown in the right panel of Figure 3 represent typical evolu-

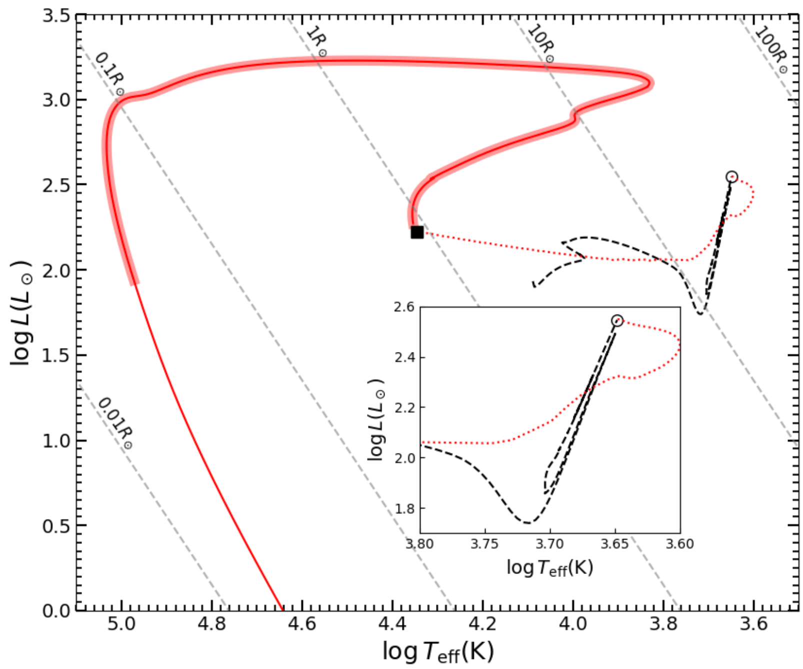

Figure 2. A typical example in constructing the SD from AGB CE channel. The black dashed line is for the evolutionary track of a $3.0M_{\odot}$ star with $Z = 0.02$ evolving from the MS to the AGB. The onset and termination of CE phase are shown in black open circle and black solid square, respectively. The produced SD mass is $0.55M_{\odot}$, and the thick red line represents the case of $\log L_{\rm He} > 0$. From Li et al. (2024).

tionary tracks for SDs with masses equal to $0.49,\ 0.55$, and $0.68M_{\odot}$, respectively. These three tracks correspond to envelopes having identical masses $(0.01M_{\odot})$. The minimum He core mass obtained through AGB CE channel is $0.48M_{\odot}$, i.e., the track shown in the thick black line. The time intervals between adjacent asterisks are 2×10^5 years. For the three thick lines, the timescales for SDs are in the range of several million years, which is approximately 100 times shorter than that of SDs from RGB channel (typically around 100 million years for a 0.46 $M_{\odot}$ SD). This could potentially explain why there is a relatively low number of massive SDs compared to canonical SDs. The tracks for SDs from the AGB CE channel closely resemble the post-AGB evolutionary tracks. Consequently, the AGB CE channel can also explain certain peculiar objects previously classified as post-AGB stars, such as hot UV-bright stars in globular cluster and inflated hot SDs (Moehler et al., 2019; Ratzloff et al., 2020; Kumar et al., 2024).

In the right panel of Figure 3, we present the observational sample on the

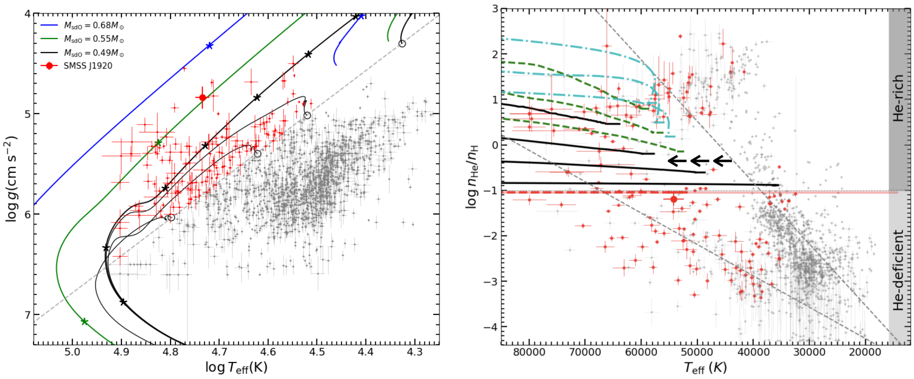

Figure 3. Right panel: The comparison between the SD evolutionary tracks and the observations in the $\log T_{\rm eff} - \log g$ plane. The observational SD samples are taken from Luo et al. (2021). Right panel: Helium abundance vs. effective temperature for the observations and SD tracks. From Li et al. (2024).

$T_{\rm eff} - \log(n_{\rm He}/n_{\rm H})$ plane. We construct various SD models with different He core masses and envelope masses, taking into account wind mass-loss from SDs as described by Krtička et al. (2016). During the AGB stage, H burning occurs in the shell and the produced SD stars generally have $\log(n_{\rm He}/n_{\rm H}) > 1$. Our models naturally reproduce the distribution of He-rich hot subdwarfs with high $\log T_{\rm eff}$. Unlike double He WD mergers and internal mixing in the hot flasher scenario, our models specifically aim to explain hot subdwarf binaries. Therefore, it would be easy to distinguish the formation channel of He-rich hot subdwarfs if there is a companion star.

4. Summary

In this study, we propose a novel pathway to SDs known as the AGB CE channel. SDs formed through this particular channel exhibit distinct structures compared to those produced by the conventional RGB channel. Consequently, there are significant variations in the physical properties of SDs between these two channels. We identify four characteristic traits of SDs originating from the AGB CE channel: high $\log T_{\rm eff}$ values, low $\log g$ values, He-rich atmospheres, and presence of companion stars. If an observational sample simultaneously exhibits all four features mentioned above, it suggests that the SD may be born via the AGB CE channel.

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