On the Surface Helium Abundance of B-type Hot Subdwarf Stars from the WD+MS Channel of Type Ia Supernovae (Postprint)

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Abstract

The origin of intermediate helium (He)-rich hot subdwarfs is still unclear. Previous studies have suggested that some surviving Type Ia supernovae (SNe Ia) companions from the white dwarf + main-sequence (WD+MS) channel may contribute to the intermediate He-rich hot subdwarfs. However, previous studies ignored the impact of atomic diffusion on the post-explosion evolution of surviving companion stars of SNe Ia, leading to the aspect that they could not explain the observed surface He abundance of intermediate He-rich hot subdwarfs. In this work, by taking the atomic diffusion and stellar wind into account, we trace the surviving companions of SNe Ia from the WD+MS channel using the one-dimensional stellar evolution code MESA until they evolve into hot subdwarfs. We find that the surface He-abundances of our surviving companion models during their core He-burning phases are in a range of , which are consistent with those observed in intermediate He-rich hot subdwarfs. This seems to further support the notion that it is possible for surviving companions of SNe Ia in the WD+MS channel to form some intermediate He-rich hot subdwarfs.

Full Text

Preamble

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On the Surface Helium Abundance of B-type Hot Subdwarf Stars from the WD+MS Channel of Type Ia Supernovae

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Abstract

The origin of intermediate helium (He)-rich hot subdwarfs remains unclear. Previous studies have suggested that some surviving Type Ia supernovae (SNe Ia) companions from the white dwarf + main-sequence (WD+MS) channel may contribute to the population of intermediate He-rich hot subdwarfs. However, these studies ignored the impact of atomic diffusion on the post-explosion evolution of surviving companion stars, which prevented them from explaining the observed surface He abundances of intermediate He-rich hot subdwarfs. In this work, by taking atomic diffusion and stellar wind into account, we trace the evolution of surviving companions of SNe Ia from the WD+MS channel using the one-dimensional stellar evolution code MESA until they evolve into hot subdwarfs. We find that the surface He abundances of our surviving companion models during their core He-burning phases range between -1 and 0, which are consistent with those observed in intermediate He-rich hot subdwarfs. This further supports the notion that surviving companions of SNe Ia in the WD+MS channel could form some intermediate He-rich hot subdwarfs.

Key words: (stars:) subdwarfs – atomic processes – diffusion

1. Introduction

Type Ia supernovae (SNe Ia) are considered one of the most reliable distance indicators due to their consistent peak luminosities. Consequently, SNe Ia are utilized to quantify cosmological parameters, which helped reveal the Universe's accelerated expansion and the dominance of dark energy (Riess et al. 1998; Perlmutter et al. 1999). SNe Ia are also employed as cosmic probes to evaluate the dark energy equation of state and its temporal evolution (Howell 2011; Sullivan et al. 2011).

Despite their importance to contemporary astrophysics, fundamental questions regarding their progenitor systems and explosion mechanisms remain under discussion (Hillebrandt & Niemeyer 2000; Leibundgut 2000; Wang & Han 2012; Maoz et al. 2014; Liu et al. 2023). Most researchers agree that SNe Ia originate in close binaries containing one carbon–oxygen white dwarf (CO WD)

(Hillebrandt & Niemeyer 2000; Branch 2004; Nugent et al. 2011; Hillebrandt et al. 2013). Progenitor models are primarily separated into single-degenerate (SD) and double-degenerate (DD) models based on the nature of the companion (Whelan & Iben 1973; Nomoto 1982; Iben & Tutukov 1984; Webbink 1984). In the SD model, the non-degenerate companion star could be a main-sequence star (i.e., the WD+MS channel), a sub-giant, a red giant star (i.e., the WD+RG channel), an asymptotic giant branch star (i.e., the WD+AGB channel), or a helium star (i.e., the WD+He star channel) (Whelan & Iben 1973; Nomoto et al. 1984; Wang et al. 2009; Wang & Han 2012; Li et al. 2023). The DD model consists of two CO WDs (Han 1998; Liu et al. 2018). While no surviving companion remains in the standard DD model, the SD model predicts that companion stars survive after the SN Ia explosion. Finding surviving companions in nearby SN remnants therefore offers a promising way to differentiate between the SD and DD models. Consequently, detailed analysis of the characteristics of potential surviving companions is believed to be useful for understanding the origins of SNe Ia (Li et al. 2017; Meng & Li 2019; Ruiz-Lapuente 2023).

Hot subdwarfs have been proposed as possible surviving companions of SNe Ia (e.g., Meng & Li 2019). These are core helium-burning stars with very thin hydrogen envelopes, generally divided into B-type hot subdwarf stars (sdBs) and O-type hot subdwarf stars (sdOs) according to their spectral features (Green et al. 1986). In the Hertzsprung–Russell (HR) diagram, hot subdwarfs are located either at the blue end of the horizontal branch (HB) or beyond that stage (Heber 2009). SdBs typically have effective temperatures between 20,000 and 40,000 K, while sdOs have temperatures between 40,000 and 80,000 K and are generally more luminous than sdBs.

Some mysteries regarding the genesis of hot subdwarfs remain. Given that a significant portion of sdB stars are found in close binaries, binary interaction processes should be responsible for their formation (Heber 2009, 2016). Detailed descriptions of how hot subdwarfs originate via binary evolution, specifically through Roche Lobe overflow (RLOF), common envelope (CE) ejection, and double He WD merger channels, can be found in Han et al. (2002, 2003).

Most hot subdwarfs exhibit peculiar chemical abundance signatures. The majority of sdBs have He-deficient atmospheres, with surface He abundance as low as a thousandth of the solar value. The sdOs display a range of surface He abundances, from one percent of the solar value to nearly pure He atmospheres (Heber 2009, 2016). Previous researchers have categorized hot subdwarfs into He-deficient and He-rich groups based on the solar helium abundance, where N_{H} and N_{He} represent the surface number densities of hydrogen and helium, respectively (Németh et al. 2012; Luo et al. 2016, 2019). He-rich hot subdwarfs are further divided into extreme He-rich (eHe-rich) stars ($\log(N_{\mathrm{He}}/N_{\mathrm{H}}) > 0$) and intermediate He-rich (iHe-rich) stars ($-1 < \log(N_{\mathrm{He}}/N_{\mathrm{H}}) < 0$). Generally, the He-rich group is believed to result from the merger of two He WDs, whereas the He-deficient group most likely originates from RLOF and CE ejection channels (Han et al. 2002, 2003; Heber 2009, 2016). However, the origin of the iHe-rich group remains unclear (Martin et al. 2017; Luo et al. 2019).

Meng & Podsiadlowski (2017) proposed a new version of the SD model for SNe Ia: the common-envelope wind (CEW) model. In this model, if the mass transfer rate between a CO WD and its companion exceeds a critical accretion rate, a CE forms around the binary system, and the WD may gradually increase its mass at the base of the CE. Based on the CEW model, Meng & Luo (2021) studied the formation of hot subdwarfs from surviving companions of SNe Ia in the WD+MS channel (Meng & Li 2019; Meng et al. 2020) and compared their results with observational properties of iHe-rich hot subdwarfs. They discovered that several observational features, such as effective temperatures and surface gravities, could be explained by hot subdwarfs from this channel. However, their models struggled to explain the observed surface He abundances of iHe-rich subdwarfs, possibly because they ignored the effects of atomic diffusion and wind mass loss from the surface of the sdB star.

Previous studies have shown that atomic diffusion and wind mass loss from the surface of an sdB star can considerably affect its surface He abundances (Unglaub & Bues 2001; Hu et al. 2011). Therefore, it is important to investigate whether including atomic diffusion and wind mass loss during the evolution of surviving companion stars of SNe Ia in the WD+MS channel could explain the observed surface He abundance of iHe-rich subdwarfs. In this work, by taking atomic diffusion and stellar wind into account, we follow the evolution of SNe Ia surviving companions from the WD+MS channel until they evolve into hot subdwarfs using the one-dimensional stellar evolution code Modules for Experiments in Stellar Astrophysics (MESA). We describe our methods in Section 2, present the results in Section 3, and provide discussion and summaries in Section 4.

2. Methods

2.1. Atomic Diffusion

Atomic diffusion refers to a group of particle transport mechanisms that alter a star's chemical composition, including radiative levitation, thermal diffusion, concentration diffusion, and gravitational settling (Hu et al. 2010). The competition between outward radiative forces and inward gravity determines an element's diffusion velocity, which varies depending on the element (Hu et al. 2010, 2011). Consequently, atomic diffusion directly impacts a star's abundance profile (Byrne et al. 2018). Because the diffusion timescale is roughly inversely proportional to density, atomic diffusion is more efficient in a star's outer layers (Deal et al. 2018). Therefore, atomic diffusion must be included to accurately predict surface abundances, particularly for high surface gravity stars like hot subdwarfs (Campilho et al. 2022).

We study atomic diffusion in hot subdwarfs from the WD+MS SN Ia channel using the stellar evolution code MESA. MESA includes concentration diffusion, thermal diffusion, and gravitational settling as standard processes activated by the `do_{{{element}}_{{diffusion}}}` flag. Atomic diffusion is computed using the formalism of Thoul et al. (1994) and Hu et al. (2011) to solve the Burgers equations (Burgers 1969). Radiative levitation is included as an optional method (Paxton et al. 2011, 2013, 2015, 2018, 2019). In this paper, we focus on surface helium abundance. Generally, radiative levitation has a negligible effect on helium but is significant for heavy elements (Hu et al. 2010, 2011). Therefore, we do not include radiative levitation in this study since calculating it in MESA is computationally expensive.

2.2. Subdwarf Models

In the WD+MS channel, a WD accretes hydrogen-rich material from its companion when the companion fills its Roche lobe on the main sequence or in the Hertzsprung gap (HG) (Meng & Podsiadlowski 2017). The WD explodes as an SN Ia when its mass exceeds the Chandrasekhar limit. The companion may then evolve into an sdB star. Since we are only concerned with the surface helium abundance during the sdB phase, we use single-star evolution rather than binary evolution calculations to construct sdB models, modeling the companion's mass transfer with a constant mass-loss rate.

We display the evolution of models with different initial masses in the HR diagram in Figure 1. We first select two main-sequence stars of 3 $M_\odot$ (model A) and 4.5 $M_\odot$ (model B) with solar abundances ($X = 0.70$, $Y = 0.28$, $Z = 0.02$) and evolve them to the HG phase. We then activate the high mass-loss rate option (`mass_{change}` in MESA) to simulate mass loss. For model A, the mass-loss timescale is 2.5×10^6 yr and the mass-loss rate is $10^{-6} M_\odot$ yr^{-1}. For model B, the mass-loss timescale is 3.98×10^5 yr and the mass-loss rate is $10^{-5} M_\odot$ yr^{-1}. We then assume an SN Ia occurs and mass loss stops. Systems with more massive WDs and more massive companions are more likely to form hot subdwarfs, which means a higher mass-loss rate and consequently a shorter mass-loss timescale. The employed mass-loss timescales and rates are comparable to those from typical binary evolution calculations for SNe Ia (Meng & Podsiadlowski 2017), and the resulting hot subdwarf stars are similar to those from binary calculations (Meng & Luo 2021).

During the mass-loss phase, companion stars lose almost all their hydrogen envelope, making diffusion effects insignificant. Therefore, we do not include atomic diffusion in our models before the SN explosion. We carry out three cases with different physical inputs. Models A0/B0 exclude both atomic diffusion and stellar wind, similar to Meng & Luo (2021). Models A1/B1 include only atomic diffusion, while models A2/B2 include both atomic diffusion and stellar wind. We use Reimers' wind to simulate mass loss from the surface of the surviving companion, with η_{Reimers} set to 0.1 (Reimers 1975).

3. Results

3.1. Evolution to the sdB Stage

After the rapid mass-loss phase, the masses of models A and B are 0.5 $M_\odot$ and 0.52 $M_\odot$, respectively, with hydrogen envelope masses of 0.02 $M_\odot$ and 0.01 $M_\odot$, respectively. The subsequent evolution of these stars is shown in Figure 1 [Figure 1: see original paper].

For model A, the star consecutively experiences the red giant branch and HB phases. Its hydrogen envelope is consumed by shell hydrogen burning during the HB phase, causing the envelope to grow gradually thinner. As the envelope is consumed, the surface temperature increases, and the star evolves to the hot subdwarf stage in the HR diagram. After core helium exhaustion, the subdwarf evolves directly to the WD branch rather than to the AGB. For model B, the star expands rapidly and enters the sdB stage about two million years after mass loss stops (see also Meng et al. 2020). Due to its larger mass, model B has a higher surface effective temperature than model A during the sdB phase. Its subsequent evolutionary track is similar to model A. The differing post-SN Ia evolutions of models A and B can be traced to the different masses of the hydrogen-rich envelope at the time of the supernova explosion; stars with thicker hydrogen envelopes follow evolution tracks more similar to isolated stars.

To compare with observations, we present $\log g$ versus $T_{\rm eff}$ in Figure 2 [Figure 2: see original paper], where some iHe-rich subdwarfs are also shown (observational data from Lei et al. 2018, 2019, 2020 and Luo et al. 2019, 2021). The iHe-rich hot subdwarf samples shown here are isolated stars. As demonstrated in Figure 1, different physical inputs do not affect the $\log g$ and $T_{\rm eff}$ evolutions of the surviving companions in the HR diagram. Figure 2 shows that the evolutionary tracks span several regions occupied by iHe-rich hot subdwarfs, suggesting that surviving companion models may explain several observational properties of iHe-rich subdwarfs, as proposed by Meng & Luo (2021).

In fact, the initial binary parameters of systems that produce SNe Ia largely determine the properties of hot subdwarfs from the WD+MS channel. Meng & Luo (2021) studied many hot subdwarf models from this channel with different initial masses and orbital periods. If the initial orbital period is longer (mass transfer occurs relatively later) and the initial mass of the companion star is larger (the surviving companion may be relatively more massive), the companion will have higher effective temperature and surface gravity in the hot subdwarf phase. Additionally, we notice that the evolutionary tracks of models A1/B1 (dashed lines) are somewhat shifted to lower surface gravities and effective temperatures compared to models A0/B0 (solid lines). This is due to the outward diffusion of hydrogen, which reduces envelope density, making the sdB star slightly larger and cooler and the envelope less gravitationally bound. However, the difference is too small to be discriminated observationally. Therefore, the location of hot subdwarf stars in HR or $\log g$-$T_{\rm eff}$ diagrams is not significantly affected by atomic diffusion, at least for those from the SN Ia channel.

3.2. Surface Helium Abundance

After the supernova explosions, the surface helium abundances of models A and B are approximately $\log(N_{\mathrm{He}}/N_{\mathrm{H}}) = -0.5$ and -0.3, respectively. The subsequent evolution of $\log(N_{\mathrm{He}}/N_{\mathrm{H}})$ depends on the physical inputs and the evolutionary stage of the stars.

In Figure 3 [Figure 3: see original paper], we show the evolution of $\log(N_{\mathrm{He}}/N_{\mathrm{H}})$ for model A (panel (a)) and model B (panel (b)), where N_{H} and N_{He} denote the surface number densities of hydrogen and helium, respectively. In panel (a), surface helium abundance increases for model A due to the first dredge-up in the red giant phase, where atomic diffusion does not take effect until surface convection ceases. Model B does not experience the red giant stage, so atomic diffusion takes effect immediately, as shown in panel (b).

For models A0/B0 (solid lines), surface helium and hydrogen abundances remain unchanged during the entire subdwarf stage, and the surface helium abundance of model A0 is consistent with observed iHe-rich hot subdwarfs. For models A1/B1 (dashed lines), as shown in previous studies (Wesemael et al. 1982; Fontaine & Chayer 1997), helium quickly settles below the photosphere within about 10^4 yr due to gravitational settling, and the surface becomes almost pure hydrogen, i.e., $\log(N_{\mathrm{He}}/N_{\mathrm{H}}) < -15$. Therefore, we do not show the full range of $\log(N_{\mathrm{He}}/N_{\mathrm{H}})$ for models A1/B1 in Figure 3.

For models A2/B2 (dot-dashed lines), helium also settles as in models A1/B1. However, $\log(N_{\mathrm{He}}/N_{\mathrm{H}})$ remains between -1 and 0 for about 1.8×10^8 yr for model A2 and 1×10^8 yr for model B2 due to stellar wind, until the stars evolve to the WD branch. In other words, the stars behave as iHe-rich subdwarfs.

Surface helium abundance during the hot subdwarf phase heavily depends on the mass of the remaining hydrogen-rich envelope after the SN explosion; generally, the less massive the envelope, the higher the surface helium abundance in the sdB phase. To compare with observations of iHe-rich hot subdwarfs, we show the evolution of models A2/B2 in the $\log(N_{\mathrm{He}}/N_{\mathrm{H}})$ versus $\log g$ diagram in Figure 4 [Figure 4: see original paper]. This figure demonstrates that companions following the supernova explosion spend most of their time in the region of iHe-rich hot subdwarfs when both atomic diffusion and stellar wind are considered. Again, the initial model parameters have great influence on the position in the $\log(N_{\mathrm{He}}/N_{\mathrm{H}})$-$\log g$ plane for our models.

3.3. Helium Abundance Profile

To demonstrate the influence of time-dependent diffusion, Figure 5 [Figure 5: see original paper] shows the helium abundance profile versus fractional mass at three different ages after the supernova explosion: 1×10^7, 3×10^7, and 5×10^7 yr. Without atomic diffusion, the helium abundance does not change in the envelope, as shown in panels (A0)/(B0). The outward movement of the helium core is due to hydrogen shell burning. With diffusion only, surface helium settles quickly and the outer layer becomes pure hydrogen, with the outer hydrogen envelope growing thicker over time, as shown in panels (A1)/(B1). With both atomic diffusion and stellar wind, although surface helium settles, stellar wind simultaneously peels off the outer layer, allowing surface helium abundance to remain at a relatively high level, as demonstrated in panels (A2)/(B2). The figure also makes clear that the interior profile is seldom affected by atomic diffusion, which works effectively only in the outer layer comprising about 1% of the stellar mass.

4. Discussion and Summary

Following Meng & Luo (2021), we used MESA to compute different hot subdwarf models with and without the effects of atomic diffusion and stellar wind. For basic models without diffusion, surface helium abundance remains constant after the supernova explosion if surface convection ceases. With atomic diffusion included, surface helium is quickly depleted when surface convection ceases. However, if stellar wind is also included, surface helium abundance can stay at the iHe-rich level throughout the sdB phase.

To simplify calculations, we used single-star evolution instead of binary evolution, ignoring some binary interactions that may impact our results. For example, in binary evolution, supernova ejecta can strip portions of the companion's envelope (Marietta et al. 2000; Meng et al. 2007; Pan et al. 2010; Liu et al. 2012; Bauer et al. 2019; McCutcheon et al. 2022), which might slightly increase the companion's surface helium abundance (see discussion in Meng et al. 2020). We evolved only two models because atomic diffusion calculations are very time-consuming in MESA. However, Meng & Luo (2021) studied many models from the WD+MS channel with different initial masses and orbital periods, and their models could cover most of the iHe-rich hot subdwarf samples. The basic conclusions based on our two models should not change with different initial models.

We used Reimers' wind for the mass-loss rate, though the physics of hot subdwarf winds may be complex (Krtička et al. 2016). We tested different constant mass-loss rates (similar to testing different wind coefficients) and found that weaker stellar wind leads to lower surface helium abundance in our models during the hot subdwarf phase. Thus, different wind models and coefficients could produce hot subdwarfs with different surface abundances, requiring more detailed future study. Moreover, surface element abundances are affected not only by stellar wind and atomic diffusion but also by other mechanisms such as surface rotation, magnetic fields, and turbulent mixing. For example, Hu et al. (2011) studied a typical 0.46 $M_\odot$ hot subdwarf with outer mixing of $\Delta M \approx 10^{-8}, 10^{-7}$, and $10^{-6} M_\odot$, reproducing observed He abundances of He-deficient subdwarfs.

Though several evolutionary scenarios for iHe-rich hot subdwarfs have been proposed—including the merger of a low-mass MS star with a He WD (Zhang et al. 2017), a post-CE system with incomplete atmospheric stratification (Naslim et al. 2012), and the late hot-flasher scenario (Miller Bertolami et al. 2008)—the formation of iHe-rich cases remains unclear. As described in Meng & Luo (2021), the companion's atmosphere may be polluted by supernova ejecta, potentially enhancing iron-peak elements on the surface of hot subdwarfs from the SN channel. It must be noted that the SN Ia channel provides only part of the iHe-rich hot subdwarfs with specific Galactic kinematic features, so it cannot be the main contributor. Thus, the origin of iHe-rich hot subdwarfs and the physical mechanisms affecting helium abundance on their surfaces remain to be investigated in detail.

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