

## The Formation of Subdwarf B Stars

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**Abstract.** We performed full binary evolution calculations and carried out binary population synthesis studies in order to investigate the formation of subdwarf B (sdB) stars via the channels of stable Roche lobe overflow (RLOF), common envelope ejection and helium white dwarf mergers. Our model is successful in the explanation of observational properties of sdB stars, e.g. we explained the orbital period – minimum companion mass ( $\log P - M_{\text{comp}}$ ) diagram, the effective temperature – surface gravity ( $T_{\text{eff}} - \log g$ ) diagram, the orbital period distribution, the  $\log(g\theta^4)$  ( $\theta = 5040/T_{\text{eff}}$ ) distribution, the mass function distribution, the binary fraction of sdB stars, the fraction of sdB binaries with WD companions, the birth rates, the space number densities, etc. We conclude that (a) the first RLOF needs to be more stabilized than commonly assumed, (b) the first stable RLOF is not conservative, (c) common envelope ejection is very efficient.

### 1. Introduction

Subdwarf B (sdB) stars dominate the ultraviolet (UV) radiation in old stellar populations, such as giant elliptical galaxies. The UV excess, or “UV upturn,” is used as an age indicator of giant elliptical galaxies via an evolutionary population synthesis (EPS) approach (Yi, Demarque & Oemler 1997) and this is important to cosmological models. The sdB stars also play an important role in the study

of the Galaxy due to their ubiquity in galactic populations (Green, Schmidt, & Liebert 1986). In stellar astrophysics, sdB stars attract more and more attention, partly due to some of them being pulsational (Kilkenny et al. 1999), and more importantly due to the puzzle of their formation to stellar evolution theory. They are considered to be core-helium burning stars with extremely thin hydrogen envelopes ( $< 0.02 M_{\odot}$ ), and most of them have masses around  $0.5 M_{\odot}$  (Heber 1986; Saffer et al. 1994), and more than half of the sdB stars were found in binaries recently (Maxted et al. 2001). Many theoretical investigations on the formation of sdB stars have been made in the past, but mainly for single sdB stars. Webbink (1984) and Iben & Tutukov (1986) proposed that the coalescence of double helium white dwarfs (WD) may lead to the formation of sdB stars. D'Cruz et al. (1996) argued that enhanced stellar wind near the tip of the first giant branch (FGB) can result in the formation of sdB stars as well, while Sweigart (1997) suggested that helium mixing driven by internal rotation makes the formation easier. However, stable and conservative mass transfer in binaries may also produce sdB stars, as shown by Mengel, Norris, & Gross (1976) with the evolution calculation of a binary system with initial masses ( $0.80 M_{\odot}$ ,  $0.78 M_{\odot}$ ) and composition  $X = 0.73$ ,  $Z = 0.001$ .

In this paper, we make an extensive study on the formation of sdB stars via full binary evolution calculations and binary population synthesis simulations.

## 2. The Model

With Eggleton's stellar evolution code (Eggleton 1971, 1972, 1973; Han, Podsiadlowski, & Eggleton 1994; Pols et al. 1995, 1998), we performed full binary evolution calculations and studied the condition for the formation of sdB stars via binary channels. Fig. 1 shows the evolutionary tracks of sdB stars, and the following binary channels are found possible.

*The first CE ejection* – If the primary star fills its Roche lobe near the tip of FGB, a common envelope (CE) (Paczynski 1976) may result from dynamically unstable Roche lobe overflow (RLOF). The ejection leaves a sdB star with a main-sequence (MS) companion.

*The first stable RLOF* – If the primary with a zero-age main-sequence (ZAMS) mass below the helium flash mass fills its Roche lobe near the tip of FGB, and if the RLOF is stable, the remnant of the primary after the stable RLOF becomes a sdB star. The sdB star has a MS companion and a long orbital period. If the primary has a ZAMS mass higher than the helium flash mass, the stable RLOF even at the Hertzsprung gap (early case B) can produce an sdB star, as shown by the detailed binary evolution calculation of Han, Tout, & Eggleton (2000).

*The second CE ejection* – This channel is similar to the first CE ejection channel, but the progenitor is a WD binary system. A shorter orbital period of a sdB star may be resulted as the WD companion of the progenitor is much smaller in radius than a MS star and the WD can penetrate much deeper into the CE to have it ejected. Therefore sdB stars from this channel have a wider orbital period range and their companions are WDs.

*The second stable RLOF* – This channel is similar to the first stable RLOF channel, but the progenitor is a WD binary system.

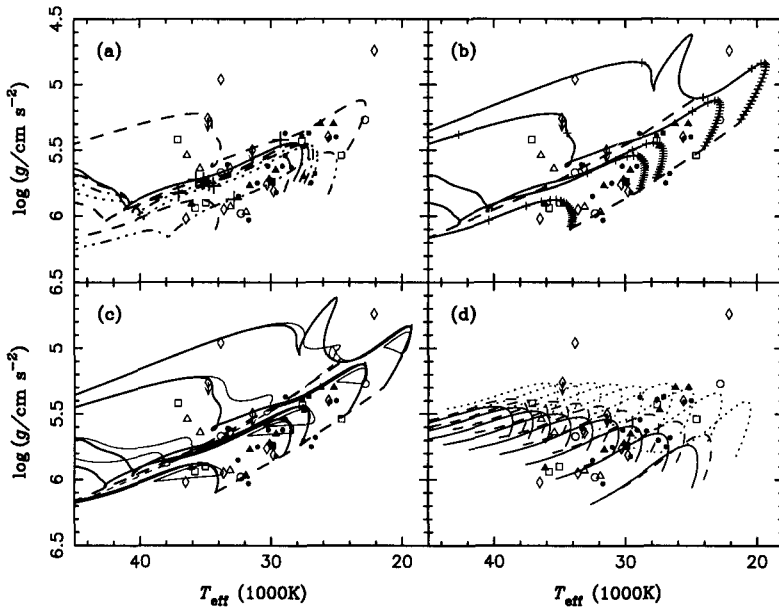


Figure 1. Evolutionary tracks of Pop I sdB stars in the  $T_{\text{eff}} - \log g$  diagram. Symbols are for observational data points of Maxted et al. (2001). Filled circles show the position of observed sdB stars with orbital periods  $P_{\text{orb}} < 1$  d, solid triangles are for systems with periods  $1 < P_{\text{orb}} < 10$  d, solid squares are for systems with  $P_{\text{orb}} > 10$  d. Circles show systems that have radial velocity variations  $dV > 40$  km/s, triangles are for systems with  $20 < dV < 40$  km/s, squares for  $10 < dV < 20$  km/s, diamonds for  $dV < 10$  km/s, where  $dV$  is the maximum difference between radial velocities measured for a particular object. Arrows indicate lower limits for  $g$ . Panel (a): tracks for 8 selected models. Crosses show the point of central He exhaustion. Panel (b) illustrates the dependence of the evolutionary tracks on the envelope mass. All models are for a ZAMS model of  $1 M_{\odot}$  and a sdB mass of  $0.46 M_{\odot}$ . The solid curves from bottom to top are for envelope masses of 0.000, 0.001, 0.002, 0.005,  $0.010 M_{\odot}$ , respectively. The left dashed curve indicates the point of central helium exhaustion, while the right dashed curve shows the locus of zero-age HB models. The age differences between adjacent crosses are  $10^7$  yr. Panel (c) illustrates the dependence of evolutionary tracks on convective overshooting. The thin solid/dashed curves do not include convective overshooting, while the solid ones do. Panel (d) illustrates the variation with sdB mass (for  $Z = 0.02$ , with overshooting). Solid curves are for an envelope mass of  $0.001 M_{\odot}$ , dashed curves for  $0.002 M_{\odot}$  and dotted curves for  $0.005 M_{\odot}$ . For each set, the curves from right to left are for sdB masses of 0.35, 0.40, 0.45, 0.50, 0.55, 0.60, 0.65, 0.70,  $0.75 M_{\odot}$ , respectively. All curves show the tracks from the zero-age HB to the point of central helium exhaustion.

*Merger of double helium WDs* – Double helium WDs may be produced after a binary has experienced two CEs, or one stable RLOF and one CE (Han 1998). The double helium WDs may coalesce due to gravitational wave radiation (GR) and the merger is a sdB star. In this channel, the sdB star is single, unlike that from previous channels.

We adopt the BPS code, which was developed in 1994 and has been updated since then (Han, Podsiadlowski, & Eggleton 1994; Han 1995; Han, Podsiadlowski, & Eggleton 1995; Han et al. 1995; Han 1998; Han et al. 2001), to investigate the binary channels for the formation of sdB stars. The main input of the code is stellar model grids. We have 3 sets of old grids for  $Z = 0.02$ , 0.004 and 0.001, which do not have convective overshooting considered and no stellar wind included implicitly. For the purpose of this paper, we calculated 6 new grids for  $Z = 0.02$  and 0.004. The new grids are smaller and only cover a small mass range appropriate for the study of sdB stars. The new grids include stellar wind and convective overshooting.

### 3. Results

For the production of sdB stars, we have performed a series of Monte Carlo simulations with the BPS code. In each simulation, we follow the evolution of a million sample binaries according to our grids of stellar models. In the simulations, we took a constant star formation rate (SFR) over the last 15 Gyr, the initial mass function (IMF) of Miller & Scalo (1979), a constant initial mass ratio distribution, and a flat distribution of initial orbital separations.

Fig. 2 shows the  $T_{\text{eff}} - \log g$  diagrams for sdB stars from all the channels in our ‘best simulation set.’ Panel (a) is without any selection effect, while in panel (b) we considered the most important selection effect in the observations of Maxted et al. (2001), i.e. the sdB candidates are selected against sdB binaries with companion spectral types G and K, and against sdB binaries with companions brighter than the sdB stars (hereinafter the GK effect). There are other selection effects as well, such as that a major fraction of the candidates are selected from a strip between zero age sdB stars with masses of  $\sim 0.5 M_{\odot}$  and the termination of core-helium burning in the  $T_{\text{eff}} - \log g$  diagram, and that the semi-amplitudes  $K$  of radial velocities of all the sdB binaries with known orbital periods are larger than 30 km/s. However, Aznar Cuadrado & Jeffery (2001) selected their candidates differently and show that some sdB stars have low effective temperatures, consistent with panel (a) of Fig. 2.

Our BPS model also gives the birth rates of type Ia supernovae (SN Ia) from different models of SN Ia. The predicted birth rate from the double degenerate model is also consistent with the Galactic SN Ia frequency.

Because of limited space, we cannot give the detailed and systematic study of sdB stars in this contribution. An extensive investigation is published elsewhere (Han et al. 2002a, 2002b).

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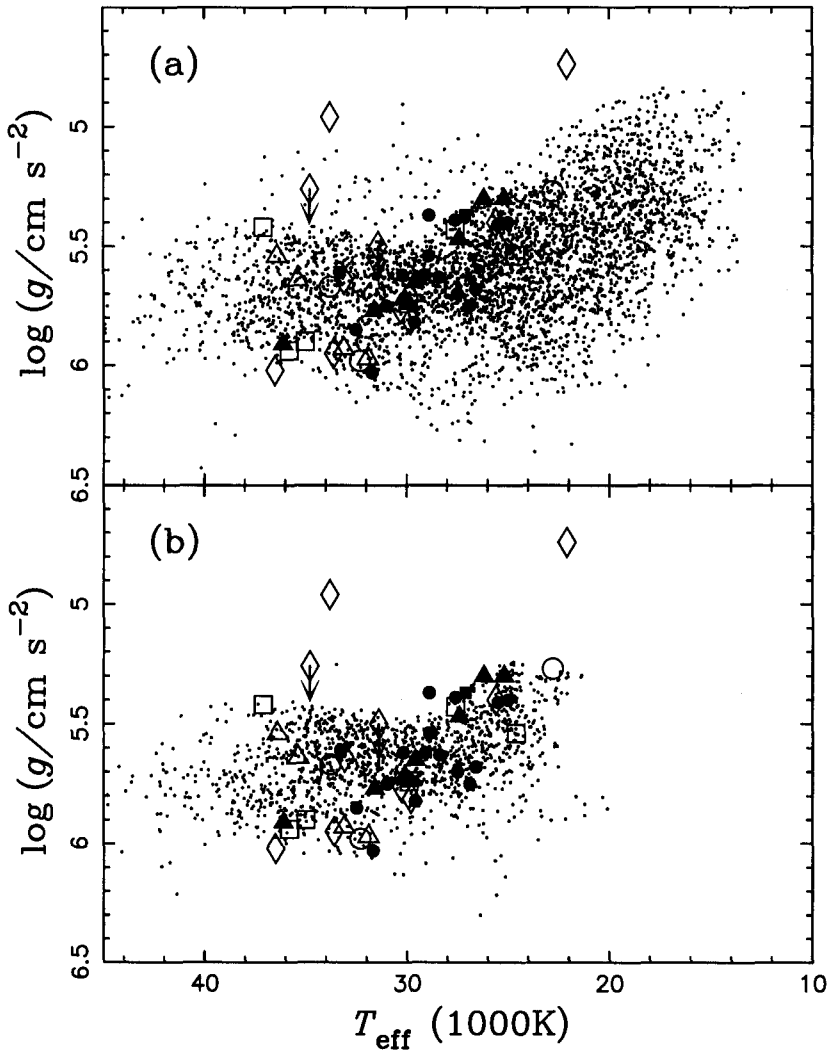


Figure 2. The  $T_{\text{eff}}$  -  $\log g$  diagram for our ‘best simulation set.’ Dots are from the simulation, other symbols are for observational sdBs (similar to that in Fig. 1). Panel (a) is without any selection effect, and panel (b) is with the GK selection effect. In producing this figure, we evolve sdB stars according to our sdB evolution model grids and with binary interactions, including RLOF, magnetic braking, gravitational wave radiation, considered. The sdB stars from CE ejection channels are assumed to have envelope masses between 0.0 and  $0.006 M_{\odot}$ , the sdB stars from stable RLOF channels have envelope masses between 0.0 and  $0.012 M_{\odot}$ , the sdB stars from the merger channel have envelope masses between 0.0 and  $0.002 M_{\odot}$ .

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