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The origin of subdwarf B stars

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Abstract

The origin of subdwarf B stars (sdBs) is unclear. Different formation channels are proposed including: close-binary evolution, helium-mixing on the red giant branch and the hot flasher scenario. Circumstantial evidence exists that sdBs can result from single star evolution in high metallicity populations. We investigate this possibility by using membership in the thin, thick disk and halo populations as a metallicity indicator. Radial velocity measurements were combined with Gaia proper motions to calculate space motions in the Galaxy. Galactic orbits and population memberships were derived. Preliminary results indicate more sdBs are members of the thin disk (86 sdBs) than of thick disk and halo (28 sdBs). Apparently single sdBs are found among all three populations. We look into the temperature distributions of the different types and discuss implication for formation scenarios.

Keywords: subdwarf B, kinematics, population membership

1. Introduction

Several different formation channels for subdwarf B stars (sdBs) have been proposed. This investigation considers the following scenarios: close binary evolution, helium-mixing on the red giant branch (RGB) and hot flasher scenarios.

Close binary evolution models are described by Han et al. (2002). One type of close binary evolution is common envelope evolution where the mass transfer rate is so high that material leaves the Roche lobe creating a common envelope. The gravitational potential energy is converted by friction to heating which forces the common envelope to be expelled leaving a close binary containing an sdB or a merger. Another type of close binary evolution is conservative mass with lower accretion rates resulting in a long period binary. It is argued that sdBs can only form through close binary evolution (Pelisoli et al., 2020).

However, some non-binary formation channels are proposed. For example, helium-mixing on the red giant branch (RGB) as described by Sweigart (1997). It is proposed that convective layers of the star penetrate the hydrogen burning shell, causing higher luminosity at the tip of the RGB which results in higher mass loss. However, the mechanism for this dredging is unknown. Another formation scenario is the hot flasher scenario which postulates that sufficient mass loss can occur on the RGB and the star experiences a helium flash on the white dwarf cooling track (Castellani and Castellani, 1993).

There is some evidence to suggest that the sdB formation rate could be metallicity dependant. This would argue against binary only formation because these channels are (almost) independent of metallicity (Han et al., 2003). Buzzoni et al. (2006) and Spriggs (2022) found that the UV excess of galaxies with super solar abundances correlates with metallicity. It is established that UV excess of galaxies is caused by sdBs (O'Connell, 1999). There is further evidence for the metallicity dependence of sdB formation from the NGC 6791 open cluster which contains 5 of 6 known sdBs in open clusters. The other sdB is found in NGC 188, both of these clusters are very old. Gratton et al. (2006) found that NGC 6791 has a super solar metallicity ([Fe/H]$= 0.32 \pm 0.032$) and NGC 188 ([Fe/H]$= 0.075 \pm 0.045$) has about solar metallicity. Knowing that all known sdBs in open clusters are in high metallicity environments supports the hypothesis that there is a metallicity dependence of sdB formation. Thus, we will investigate the hypothesis that a significant portion of sdBs do not form through a binary system channel.

2. Method

The surface abundances of sdBs are heavily modified by diffusion. To identify possible indicators of single star evolution in a sample of sdBs the population membership was used as a proxy for metallicity. To classify the population membership the classification method developed by Pauli et al. (2006) was adapted for sdB samples. It was calibrated using a sample of main sequence stars with known metallicities. Galactic orbits were calculated from galactic coordinates (X,Y,Z) and velocity components (U,V,W), see Fig. 1. From these the orbital eccentricity e and angular momentum J_Z in the Z direction were extracted from the orbits to create $U-V$ plots (Fig. 2) and J_Z-e plots (Fig 3). Meridional plots of the orbits of the stars (Fig. 1) were also used to classify the samples as the Z displacement and patterns were indicative of specific populations.

Using these kinematic indicators a classification method was devised for the likely population memberships of sdB stars. A classification value c is assigned which is the sum of the individual c values from each plot determined by position within the plot. c of -1 was given for any star that lay within the 2 σ contour on the $U-V$ plot, within Region A of the J_Z-e plots or with a 100-300pc Z displacement on the meridionial plots. c of +1 was given to the stars which lay beyond the 2 σ contour on the $U-V$ plot, within Region B of the J_Z-e plots or with a 800-1300pc Z displacement on the meridionial plots. c of +2 was given to the stars which lay within Region C of the J_Z-e plots or with a pc larger than 1300 on the meridionial plots. A final c value of 0 determined a thin disk star, 1-3 a thick disk and 4+ a Halo.

3. Results

Stars from three radial velocity surveys of sdBs were classified using our criteria: SPY (Napiwotzki et al., 2004), Maxted (Maxted et al., 2001) and Copperwheat (Copperwheat et al.,

Table 1: Classification results. The fraction of stars by population membership and binaries is indicated.

Sample	Thin disk (%)	Thick disk (%)	Halo (%)	Binary fraction (%)
SPY	77	18	5	39
Maxted	80	15	5	49
Copperwheat	83	14	3	49

2011) samples. The SPY sample is a by-product of a radial velocity survey of white dwarfs (Napiwotzki et al., 2020). Maxted et al. (2001) selected targets from the PG survey. The Copperwheat sample combines stars from the EC and PG surveys. We included only binaries with orbital solutions.

3.1. Classification results

Results from the classification and binary fractions are presented in Table 1. Most stars are members of the thin disk, with a slightly smaller fraction in the SPY sample. The binary fractions are similar for all populations indicating no metallicity dependence. The temperature distributions for the three samples are presented in Fig. 4. Most binaries are found at middling temperatures (25. . . 30 kK), while the single sdBs tend to have higher temperatures.

A Kolmogorov-Smirnov test was conducted to check for any statistical evidence of a difference in the temperature distributions between the different samples. We find that there is no statistical evidence of a difference between the SPY and Maxted temperature distributions, with a p value of 0.822. Following from this, we test the singles against binaries for the combined SPY and Maxted samples and find a p value of 0.000633, showing evidence of a difference between the two distributions.

Fuhrmann (2008) derived the local space density of low mass thin disc and thick disk stars: $N_{\text{thick}}/N_{\text{thin}} = 0.20 \pm 0.02$. Correcting for the different scale heights of the populations yields very similar surface densities for both populations. It is remarkable that the number of thick disc sdBs is much smaller than the number of their thin disc counterparts with the ratio being five. Some selection effects might skew the ratio. The deeper SPY sample (median $z = 1.2\,\text{kpc}$) has indeed a lower ratio ($N_{\text{thin}}/N_{\text{thick}} = 4.3$) than the shallower Maxted sample (0.48 kpc; $N_{\text{thin}}/N_{\text{thick}} = 5.3$), but this trend is not strong enough to eliminate the effect seen. A more thorough evaluation is in progress. This lower productivity indicates that sdB formation is indeed metallicity dependent.

4. Conclusions

The classification of the population membership of sdBs suggests that they are mostly thin disk. It was expected that most single sdBs are members of the thin disk. However, we do not find significant differences between binary fractions of thin disk and thick disk/halo sdBs.

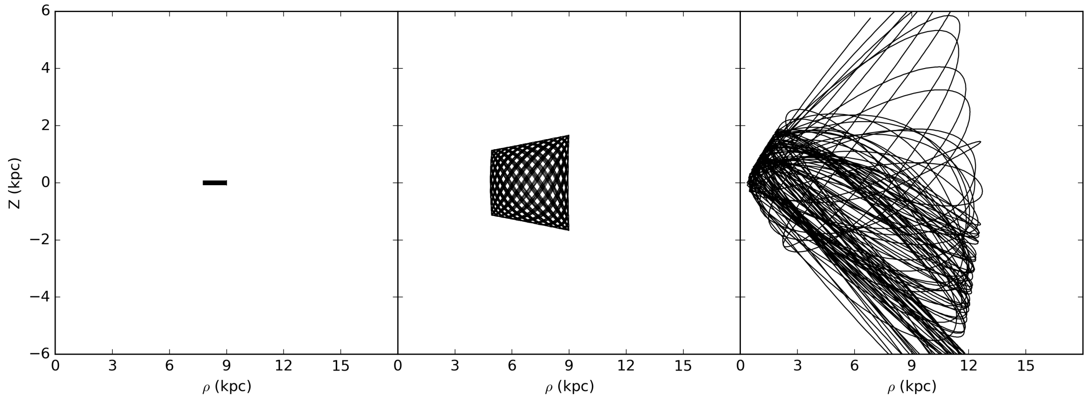

Figure 1: These are the typical meridional plots of orbits for (left) thin disk, (middle) thick disk and (right) halo stars from our sample. The axes show displacement in the Z axis and $\rho = \sqrt{X^2 + Y^2}$.

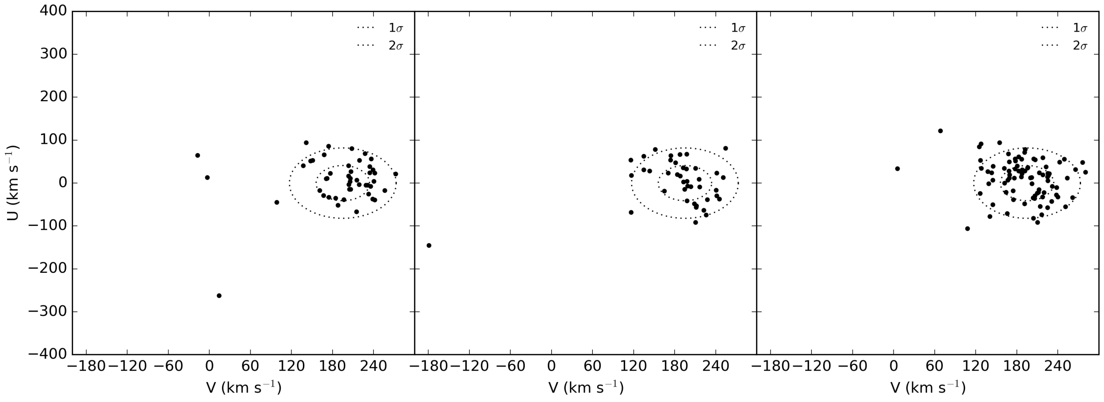

Figure 2: $U - V$ plots for the SPY (left), Maxted (middle) and Copperwheat (right) samples, the regions represent the 1 and 2 σ contours, this plots scales is given in the same scale as that in the Pauli et al. (2006) paper.

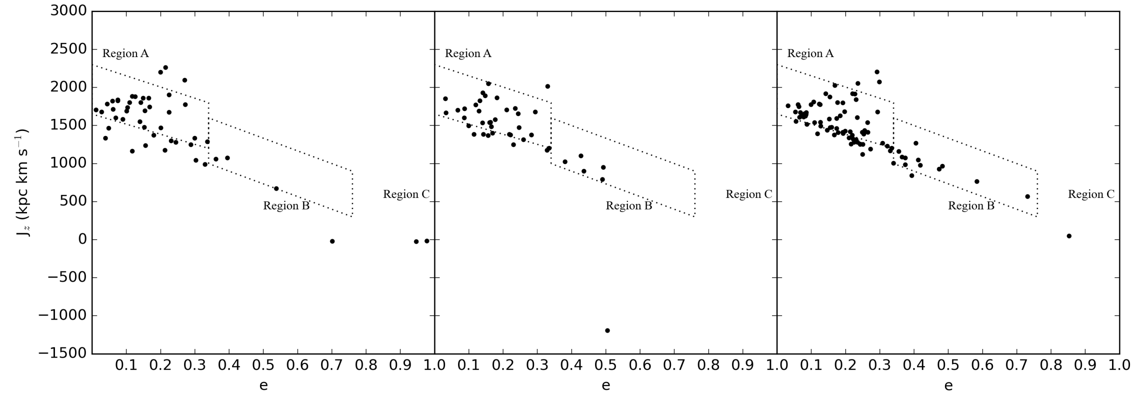

Figure 3: $J_z - e$ plots for the SPY (left), Maxted (middle) and Copperwheat (right) samples with the same regions as in Pauli et al. (2006). Region A denotes where thin disk stars are typically found, Region B contains thick disk stars and halo stars are found in Region C – everywhere else.

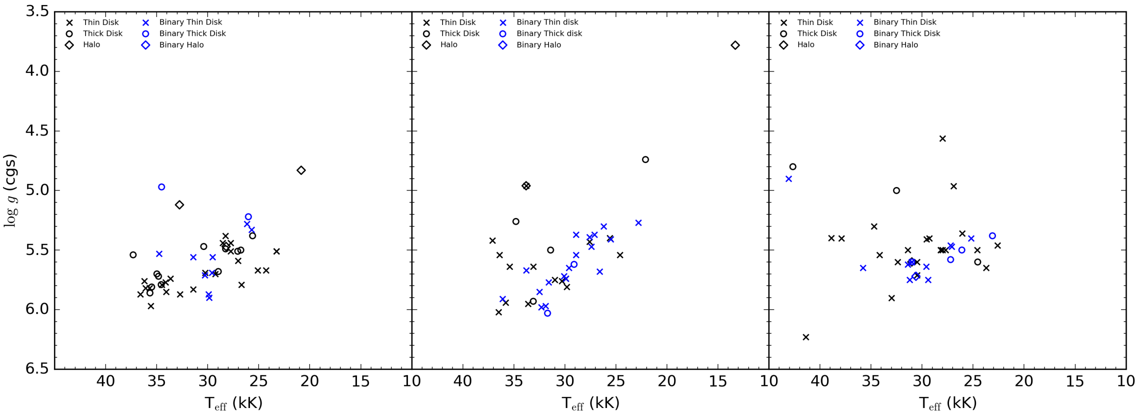

Figure 4: Kiel diagrams for the SPY (left), Maxted (middle) and Copperwheat (right) samples. Population membership and binary status are indicated.

This is inconsistent with the hypothesis of a metallicity dependent formation rate. On the other hand we found a lower production rate for the thick disk which would point to a metallicity dependence. An initial analysis of the temperature distributions found a difference between single and binary sdBs. This indicates that a number of the single sdBs could be the result of a hot flash, it is also possible that this is consistent with a merger scenario as in Han et al. (2003). Therefore we will investigate this further.

Further Information

Author contributions

CA carried out the research as part of this MSc project. RN is his supervisor.

Conflicts of interest

The authors declare no conflict of interest.

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