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SUBDWARF B STAR EVOLUTIONARY SYSTEMATICS, CONUNDRUMS AND CAUTIONARY REMARKS *

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Abstract. We examine some of the systematics of different types of subdwarf B stars – short-period sdB+WD binaries, short period sdB+MS binaries, composite spectrum systems and apparently single stars – using recent results from our ongoing spectroscopic surveys and from asteroseismology, 2MASS photometry and open cluster color-magnitude diagrams. There are a wide variety of puzzles still remaining to be solved before we understand all the details of subdwarf B star formation and evolution.

Key words: binaries: close – stars: fundamental parameters – stars: EHB and post-EHB – stars: subdwarfs

1. INTRODUCTION

For several years, we have been collecting homogeneous stellar spectra of bright ($V \lesssim 14.4$) sdB stars using both the MMT blue spectrograph and Steward Observatory's 2.3 m Bok telescope. Accurate radial velocities derived from individual MMT spectra (1 Å resolution, 4000–4950 Å) are used to identify sdB binaries and determine precise orbital parameters (Green, For & Hyde 2005). We also shift multiple spectra for the same star to the rest velocity and combine them into a single high-S/N MMT spectrum for optical abundance analysis (see Fontaine et al. 2006). Our 2.3 m survey has much lower resolution ($\sim$9 Å, 3615–6900 Å) and was originally intended solely for identification and homogeneous classification of sdO and sdB candidates. However, when we recently compared the effective temperatures, gravities and helium abundances derived from combined MMT spectra vs. similarly combined 2.3 m spectra for the same stars, we found no systematic differences, given sufficient S/N for both ($\sim$ 200–300).

We now have homogeneous parameters for 115 sdB and sdOB stars from MMT spectra, and we will soon have comparable parameters derived from 2.3 m spectra

*Observations reported here were obtained at the MMT Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.

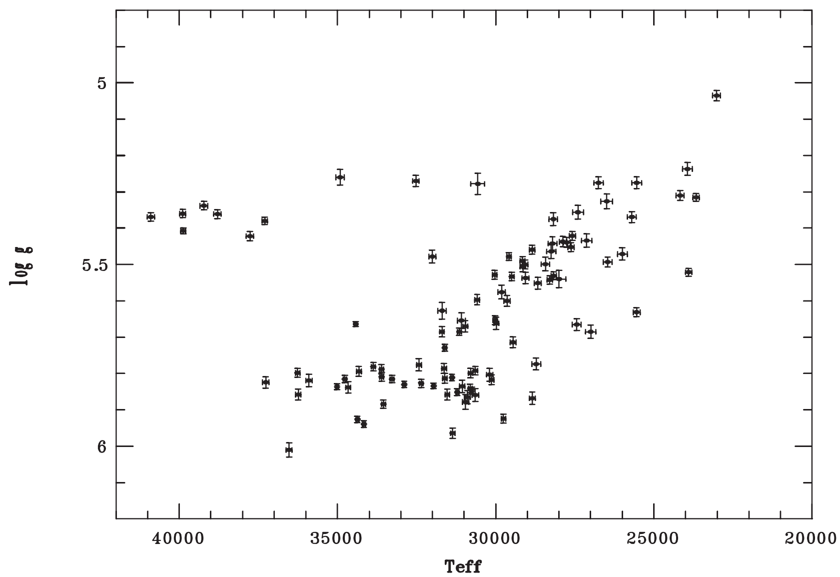

Fig. 1. The log g vs. T_{eff} diagram derived for 100 homogeneous, single-lined sdB stars in our MMT sample. The error bars are twice the formal errors of the fit.

for an overlapping sample of more than 200 stars. In sections 2 and 3, we will use the temperatures and gravities derived for our current MMT sample to show how such information can eventually help illuminate our ideas about sdB formation and evolution, particularly when combined with the new results just beginning to be uncovered by asteroseismology.

In section 4, we use 2MASS* photometry in combination with optical photometry to highlight another puzzle involving the distribution of low-mass main-sequence secondaries in sdB binaries. Finally, we reconsider the problem of representative samples of disk EHB stars in section 5. Using an infrared-selected (2MASS) hot star sample plus evidence from the color-magnitude diagrams of the old open clusters NGC 6791 and NGC 188, we investigate the cool end of the EHB region, which presents its own problems.

2. TEMPERATURE VS. GRAVITY RESULTS

Figure 1 shows the gravity vs. effective temperature diagram for stars in our MMT sample that do not have composite spectra. Fifteen sdB stars (mostly pulsators) fainter than our original magnitude limit were excluded in an effort to make this sample more representative. To the extent that this diagram truly is representative, the nonuniform distribution of stars must be reflecting significant details about their evolution. Additional data, e.g., stellar masses, will be needed before we can fully understand why these stars are distributed the way they are.

The nonuniformity shouldn't be too surprising, since we already know that several different scenarios can produce sdB stars. In fact, Figures 2 and 3 show, for the first time, that the distribution of apparently single sdB stars appears to

* http://www.ipac.caltech.edu/2mass

Table 1. Results from asteroseismology.

Pulsator	$T_{\rm eff}$	log g	Mass
PG 0014+067	34126 ± 165	5.769 ± 0.030	0.490 ± 0.019
PG 1047+003	34768 ± 112	5.815 ± 0.019	0.490 ± 0.014
PG 1219+534	33604 ± 125	5.809 ± 0.024	0.457 ± 0.012
Feige 48	29582 ± 135	5.478 ± 0.023	0.460 ± 0.008

be somewhat different from that of short-period binary sdB stars. For example, 30% of the single sdB stars lie in a relatively dense "foot" between $5.75 < \log g < 5.90$ for $T_{\rm eff} > 33\,000$ K, that is almost entirely missing in the binary distribution. However, the rest of the single stars are widely scattered over all the regions where the binaries occur. Another interesting feature is that short-period binaries with main sequence companions occupy only a small area in the middle of the range of sdB+WD binaries (except for one hot outlier, HS 2333+3927, which Heber et al. (2004) suggested might have an unusually small mass for an sdB star). It will be interesting to see if this holds up when larger samples are available, since there is no obvious reason why it should be so.

3. ASTEROSEISMOLOGICAL MASSES

Both single star evolution with enhanced mass-loss and binary mass transfer followed by common envelope ejection are expected to produce 0.46 to 0.49 $M_\odot$ sdB stars, since that is the mass range near the first red giant tip where helium can ignite in stripped stellar cores. In contrast, mergers of He-core white dwarfs are expected to produce single sdB stars with a much wider range of masses. Asteroseismology is just beginning to provide an independent check of this crucial parameter. Recent results from Charpinet and collaborators (Brassard et al. 2001; Charpinet, Fontaine & Brassard 2003; Charpinet et al. 2005a; Charpinet et al. 2005b) are listed in Table 1. Radial velocities were derived from multi-epoch spectra for each of the four objects, with a typical precision of $\sim$2 km s^{-1}. The velocities indicate that PG 0014+067, PG 1047+003 and PG 1219+534 are single stars, consistent with other similar stars in Figure 2, while Feige 48 is a binary, as previously discovered by O'Toole, Heber & Benjamin (2004).

All four asteroseismological masses are consistent with a He core flash at, or during evolution away from, the tip of the first red giant branch. This is particularly gratifying in the case of the binary, since this is the only known way that such a binary could have formed. The values for the single stars do not, by themselves, rule out the merger theory, particularly since all three refer to essentially the same point in the log g vs. $T_{\rm eff}$ diagram. However, Figure 2 shows a distinct lack of stars scattered above and below the horizontal sequence of hot stars at log $g \sim 5.8$, that would correspond to higher and lower masses. Therefore, it seems that mergers cannot be an important evolutionary channel for sdB stars hotter than $T_{\rm eff} = 32\,000$ K. It will be very interesting for the merger theory to see what asteroseismology can tell us about the masses of single stars on the right side of Figure 2!

4. A SURPRISING RESULT FROM 2MASS PHOTOMETRY

So far, we have only discussed sdB stars with non-composite spectra, i.e., those whose optical spectra show no absorption lines from a cool companion. Stark

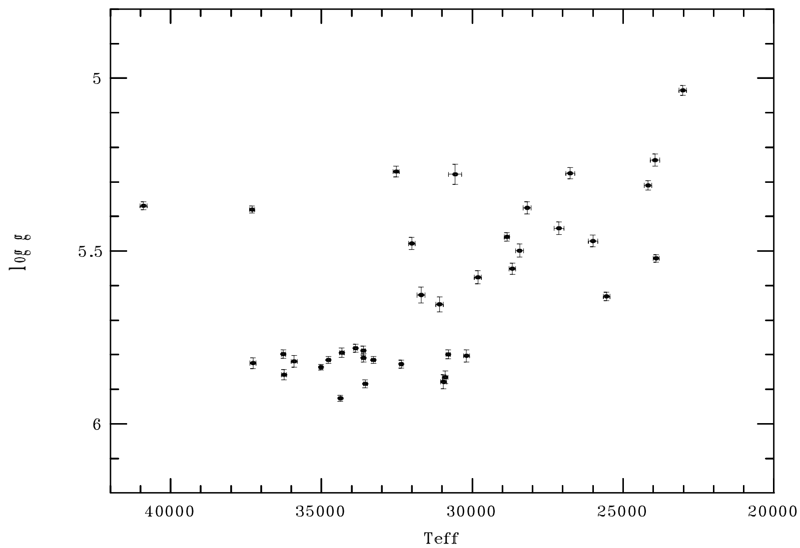

Fig. 2. The log g vs. $T_{\rm eff}$ diagram for the subsample of apparently single stars in Figure 1, i.e. those which show no significant radial velocity variations, reflection effects, absorption lines or detectable IR flux from a cool companion.

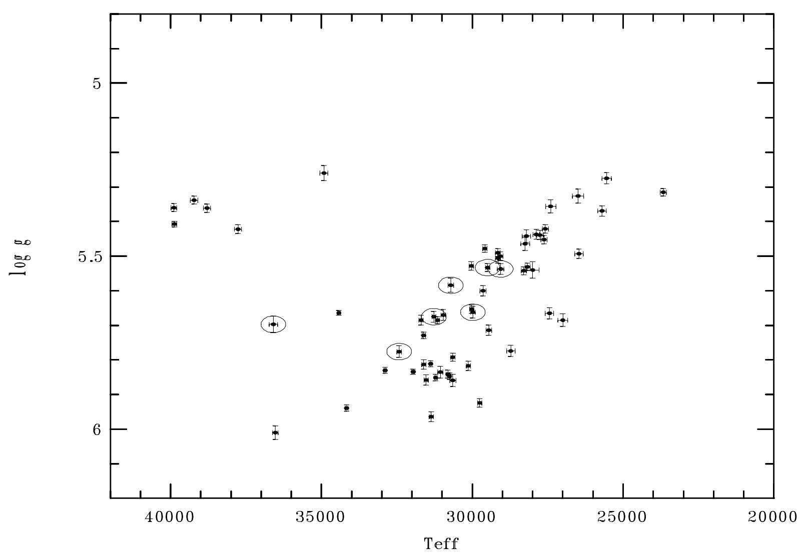

Fig. 3. The same as Figure 2, except only known short-period binary stars from Figure 1 are plotted. The seven circled objects have main-sequence secondaries, while nearly all the rest are believed to have white dwarf companions.

& Wade (2003) demonstrated that about 1/3 of sdB stars have main-sequence companions of type F, G or K, that are easily detected using a combination of optical and 2MASS infrared photometry. More recently, Green, For & Hyde (2005) showed that there is a surprising dichotomy in the $V{-}J$ vs. $J{-}H$ two-color plot

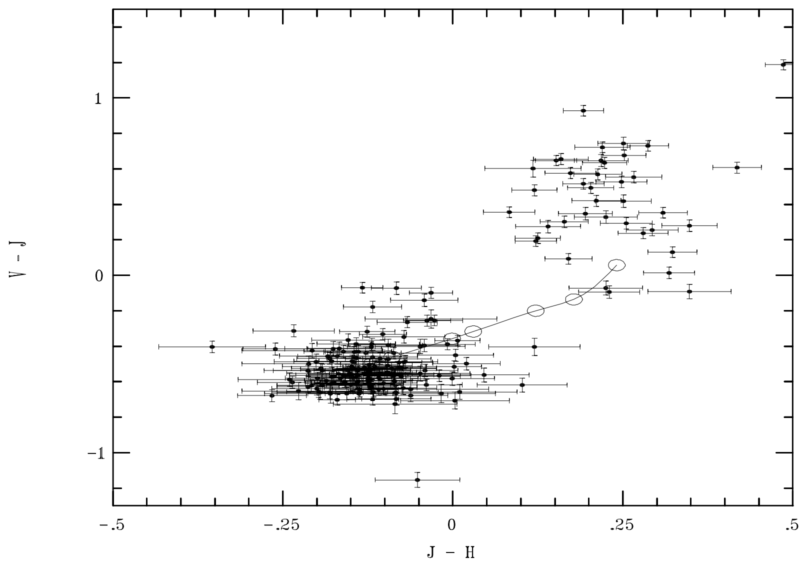

Fig. 4. V–J vs. J–H plot of spectroscopically confirmed sdB stars with V<14.4 and $E_{B-V} \leq 0.05$. The curve between the two clumps illustrates how the color of a typical composite sdB star would vary with the mass of the main-sequence secondary; the open circles mark (from upper right to lower left) companion masses of 0.70, 0.60, 0.54, 0.37, 0.26 and 0.18 $M_\odot$ (see text).

between sdB+MS binaries whose secondaries are detectable in optical spectra and all the rest (single stars and short-period binaries with invisible companions).

We have updated this result in Figure 4, having added several more stars, and the conclusions remain the same: (1) there is a significant color gap between the composite spectrum sdB stars in the upper right and all the other sdB stars at the lower left, that cannot be explained by selection effects, (2) none of the composite spectrum stars investigated so far have orbital periods shorter than many months to several years and (3) all of the sdB binaries with periods of the order of a few hours to several days fall in the lower left of Figure 4 along with the apparently single sdB stars, including the seven known sdB binaries with dwarf M3–M6 companions.

To determine the size of the gap between sdB stars with mid-M companions (in the lower left group) and those with companions of spectral types F, G or K (in the upper right), we calculated expected colors for composite stars over a range of secondary masses. Starting with a typical sdB primary having M_V = 4.5, V–J = –0.50 and J–H = –0.12, we used observed colors and magnitudes corresponding to empirically derived lower main-sequence masses from K8 to M6 (Kirkpatrick & McCarthy 1994; Henry & McCarthy 1993), to compute the combined colors (open circles). The results show that the color gap corresponds to a mass gap of about 0.3 $M_\odot$. Does this mean that nearly all sdB progenitors with main-sequence companions originally more massive than about 0.35 $M_\odot$ were able to achieve a stable mass transfer of more than 0.4 $M_\odot$ to their companions? Once again, the systematics of a large sample of sdB stars have provided a powerful clue for the formation and evolution of these stars.

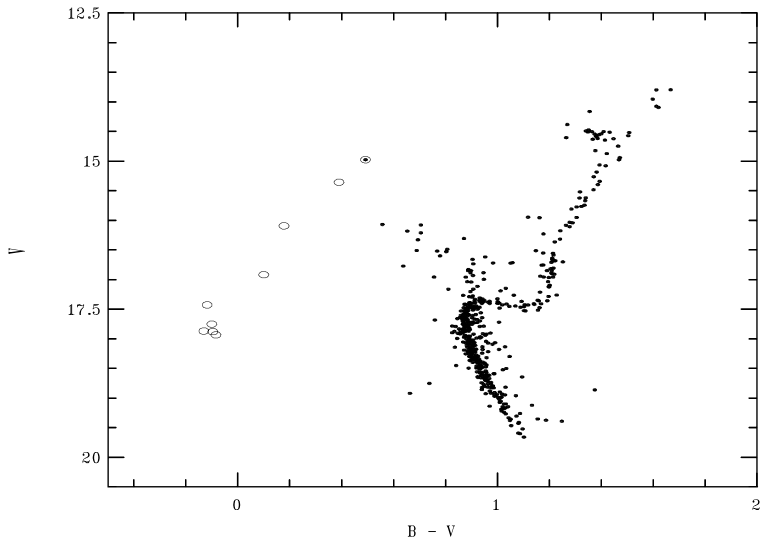

Fig. 5. NGC 6791 CMD for proper motion members (filled dots: Cudworth 1994 and private communication) and radial velocity members (open circles: Green et al., in preparation), with photometry by Kałużny & Rucinski (1995).

5. REPRESENTATIVE SAMPLES OF EHB/SDB STARS

Detailed conclusions concerning the evolutionary histories of sdB stars will not be possible in the absence of large, homogeneous, precise and *representative* samples of EHB stars. We attempted to make Figure 1 more representative by requiring a magnitude-limited sample. We will soon achieve an improved sample, following the completion of our homogeneous, low resolution survey of every known sdB brighter than $V = 14.4$. But it is doubtful that even this sample will be truly representative, because of selection effects in the identification of known sdB stars. SdB stars are often chosen spectroscopically, which discriminates against composite sdB stars with brighter F, A, or even B main-sequence companions (as is well known). Selection effects should be more straightforward for a sample of sdB stars and composite sdB stars chosen by their UV flux, but this method requires complex follow-up to separate the sdB stars from sdO, main sequence B, post-AGB, BHB stars, etc., and it does not solve a key problem: a representative sample of sdB stars (canonical spectroscopic definition) won't necessarily help us understand all about EHB stars. What we really need are representative EHB samples including sdB, sdOB and other related hot stars, i.e., all those that are produced by processes similar to those that create sdB stars. However, there is no good definition of the hot and the cool limits for disk EHB stars.

Uli Heber (2006) has provided evidence that a number of cooler sdO stars should more properly be identified with EHB stars than with post-AGB stars. For a relatively unbiased look at the opposite end of the sdB sequence, consider the color-magnitude diagram for the old, metal-rich open cluster NGC 6791.

NGC 6791 and the similar cluster NGC 188 (not shown) are the only two disk clusters known to contain sdB stars. Both clusters also contain more luminous stars extending towards cooler temperatures along an apparent blue horizontal branch, as seen in Figure 5. All of the cluster BHB stars are proper motion and/or radial velocity members, and therefore must surely be related to the sdB stars. Yet many of these cooler stars were not detected by the UIT surveys that found all the cluster sdB and sdO stars (Landsman et al. 1998). This means that even UV-selected samples will be affected by selection effects, if the goal is to find all of the relatives of sdB stars, determine their relative proportions and understand how they are related.

Another noteworthy point concerns the total distribution of the hot stars in these two disk clusters. About half are located in a small clump in the EHB region, while the other half are scattered thinly all along the BHB. This is quite different from what is found in globular clusters, where there are typically hundreds of stars along the upper horizontal branch (either the red horizontal branch, RR Lyrae strip, BHB, or some combination), but never more than a handful of EHB stars, if indeed, there exist any at all. We believe that the very different distributions between disk and halo EHB/BHB stars very likely indicate different formation histories.

In an effort to get a different perspective on the true proportions of hot EHB stars, one of us (E.M.G.) has experimented with a 2MASS-selected sample. Of the 62 197 2MASS point sources with $J < 14.6$, $-0.35 < J\text{–}H < 0.00$ and $-0.5 < J\text{–}K < -0.05$, there are 1550 with declinations north of –5°, galactic latitudes greater than 30°and E_{B-V} (max) < 0.10, including a number of previously known sdO and B stars. Spectra for 78 new objects have now been obtained in combination with our 2.3 m low resolution survey (section 2). This pilot study turned up 16 new sdB/sdOB stars, 3 sdO stars, 22 main-sequence B stars and 37 BHB stars between about 22 000K and 10 000K. We presume that most of the BHB stars are halo objects since their distribution along the BHB resembles that in globular clusters, but the old open clusters prove that at least a few of the BHB stars could be disk objects. This means that we cannot define a cutoff temperature for the cool end of the disk EHB at 22 000 K, or 20 000 K, or even 16 000 K, without excluding a number of related metal-rich BHB stars. (Of course, it will be tedious to identify them in the field, as they will be far outnumbered by halo BHB stars in most data sets).

Winter (2006) has found a very similar EHB/BHB distribution from his analysis of photometrically-selected SDSS spectra; he also finds the density of stars thins out at the cool end of the sdB sequence, but then rises again as the EHB merges into the tail of what appears to be the halo BHB. The distributions in both our 2MASS sample and Winter's SDSS sample confirm Newell's (1973) results for blue field stars, including the same low density region near 21 400 K that was identified as the second of the two famous "Newell gaps".

6. CONCLUSIONS

We conclude that precise, homogeneous, representative surveys of the fundamental parameters of EHB stars contain important information about the evolutionary histories of sdB stars. At a minimum, it will be necessary to understand the signficance of the patterns in the log g vs. $T_{\rm eff}$ diagram for each different type of sdB star. For another example, we showed how precise temperatures plus asteroseismological gravities and masses appear to rule out mergers as an important formation channel for at least the hotter sdB stars.

We further conclude that the unexpected color gap between very short period sdB stars with mid-M type main-sequence secondaries, and the much longer period systems with F, G or K type secondaries, corresponds to a mass gap in the approximate range between 0.35 and 0.65 $M_{\odot}$, although the significance of the gap is not yet clear.

Using the color magnitude diagram for members of the old disk cluster NGC 6791, and also a 2MASS-selected sample of hot stars, we have revisited the problem of obtaining representative samples of disk EHB stars. Although it will be difficult, we suggest that stars both hotter and cooler than those in typical "sdB" samples need to be included in future investigations, in order to get a clearer picture of EHB evolution. Lastly, we caution against assuming that halo EHB stars are produced by the same formation mechanisms as their disk counterparts, since the two types of horizontal branches have such widely different luminosity and temperature distributions.

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