Stars and their variability observed from space
C. Neiner, W. W. Weiss, D. Baade, R. E. Griffin, C. C. Lovekin, A. F. J. Moffat (eds)

HOT SUBDWARF STARS AND BINARY EVOLUTION

D. Brown[1]

Abstract. Hot subdwarf B stars are extreme horizontal-branch core-helium burning stars having masses of about $0.5\,\mathrm{M}_{\odot}$, and surrounded by very thin inert hydrogen envelopes of mass of $M_{\mathrm{env}} \leq 0.02\,\mathrm{M}_{\odot}$. They are thought to be formed when they lose most of the their hydrogen envelopes during the RGB phase of evolution, just before they ignite their He cores. The mechanism by which such rapid mass loss occurs is still not fully determined, but it is suspected that binary interactions via RLOF play an important role in their formation, at least in the formation of hot subdwarf stars in the Galactic field, where most sdB stars are found in binary systems. However, the fraction of binary sdB stars in globular clusters is very small, so other mechanisms, perhaps He enhancement via AGB-star ejecta in clusters that have multiple populations, might play a role in their formation, this time from single-star progenitors. Studies carried out using binary population synthesis from a theoretical point of view, following that of Han et al. (2002, 2003) and Han et al. (2007), can reveal much about the formation channels of such EHB stars, and the study described here builds on that, taking into account different chemical abundances (metallicities). Asteroseismological studies of pulsating sdB stars have also contributed greatly to the determination of sdB star parameters, especially stellar masses, which has greatly helped astronomers to understand such stars. A comparison with theory is carried out using high-speed photometry.

Keywords: Stars: sdB, binary, methods: asteroseismology

1 Introduction

The formation mechanism(s) of extreme horizontal branch (EHB) hot subdwarf (sdB/sdO) stars in the Galactic field or in globular clusters (GCs). Such stars typically have He-core masses of about $M_{\mathrm{c}} \sim 0.50\,\mathrm{M}_{\odot}$ (depending on metallicity, Z) and are surrounded by very thin inert hydrogen envelopes of $M_{\mathrm{env}} \leq 0.02\,\mathrm{M}_{\odot}$. Han et al. (2002, 2003) have presented a persuasive analysis of the binary channels suspected of producing sdB stars: 1) the CE (common envelope) binary channel, whereby the sdB progenitor experiences unstable mass transfer and produces a CE which is later ejected, and which tends to produce sdBs in binary systems with short periods of about 0.1 d–10 d, substantiated by observations from Maxted et al. (2001); 2) the stable RLOF (Roche-lobe overflow) channel, where mass transfer is stable from donor to gainer, resulting in longer-period binaries with periods peaking at about 830 d, some having orbital periods > 1100 d (Chen et al. 2013); and, 3) the merger of two He WDs (white dwarfs) in a binary to produce an sdB star. Han et al. (2002, 2003) find that the sdB mass distribution, though sharply peaking at about $0.45 - 0.5\,\mathrm{M}_{\odot}$, can be much broader, with a range of 0.3 – $0.8\,\mathrm{M}_{\odot}$. Using asteroseismology methods to study pulsating sdB stars such as EC 14026 pulsators, Fontaine et al. (2012) obtained an empirical mass distribution, including a low-mass wing component, to constrain and verify such theoretical models. Moreover, data from *Kepler/K2* (and also from *CoRoT*) have provided the precision and resolution in photometry necessary to identify pulsation modes, and thence to probe the internal structure of pulsators and determine other stellar properties. Among the many interesting findings that may fit with theoretical predictions is one dealing with intermediate-mass sdB progenitors. One possible evolutionary scenario of a low-mass sdB + WD close binary (Silvotti et al. 2012) along with asteroseismological studies by Hu et al. (2008) indicates a progenitor intermediate-mass star of mass $2.0\,\mathrm{M}_{\odot} - 2.5\,\mathrm{M}_{\odot}$. Binary population synthesis simulations at different Z carried out by Brown and building on – and in collaboration with – Han et al. (2002, 2003) and Han et al. (2007) for Z=0.02, indicate a moderate number of low-mass hot subdwarf stars evolving from intermediate mass progenitor stars, as seen in areas below the ZAHeMS (in $\log_{10} g$ - T_{eff} diagrams).

[1] Vatican Observatory, V-00120 Città del Vaticano, Europe

2 Methodology

Detailed single and binary evolutionary and binary population synthesis calculations have been conducted by Brown following the methodology of Han et al. (2002, 2003), done originally for Z =0.02 and for sdBs in the Galactic field, in order to explore a greater range of metallicities: Z =0.0001, 0.001, 0.02, 0.03, 0.04, 0.05, mainly to examine EHB and sdB formation in different chemical environments, such as in the Galactic field. Stellar models (MS-RGB-HB-AGB phases, along with specially constructed EHB models with different core and envelope masses) have been constructed and calculations performed for the evolution of single stars and single binaries using an updated version of the stellar evolution code of Eggleton (1971, 1972, 1973), supplemented by the opacity tables of Chen & Tout (2007). The resulting grid of stellar models, for each Z, then serves as input for the binary population synthesis code of Han (1995, 2000), which is able to evolve an entire stellar population over time, including binaries, by using an interpolation routine to account for mass loss through RLOF. In this study, the best fitting parameters of Han et al. (2002, 2003) are then used to examine the evolution of a population of given metallicity Z.

3 Results

Simulations have been conducted using simple stellar populations, and then using the methodology of Han et al. (2002, 2003), first of all to construct a composite population (consisting of one population at 13 Gyr with a 5 Gyr sub-population) in order to study the Galactic field. They yield a high number (75–90%) of hot subdwarf stars in binary systems for Z=0.02, comparable to that of Han et al. (2002, 2003). With selection effects taken into account, their results are consistent with those of Maxted et al. (2001) and Napiwotzki et al. (2004) which indicate a substantial number of hot subdwarf stars in binary systems – of the order of 70% and 42%, respectively. One application of the simulations at different Z is the ability to account for non-canonical-mass hot subdwarf stars that are found below the zero age He main sequence (ZAHeMS), such as those seen in Fig. 1 (left). The Figure shows two ages (for a Z = 0.03 single stellar population [SSP]: 1.995 Gyr and 11.220 Gyr, respectively) for which low-mass sdBs in their post He-core burning phase of evolution are present below the ZAHeMS. Such objects are produced through the 1RLOF, 1CE+, 1CE-, 2CE+, 2CE-, 2RLOF, or merger channels, from progenitor stars of masses close to the transition between low-mass and intermediate-mass stars, which itself depends on metallicity. This suggests that low-mass sdB stars ($0.30 - 0.40\,\mathrm{M}_\odot$) form from intermediate-mass ($\sim 2.0\,\mathrm{M}_\odot$) stars which have ignited their non-degenerate He-cores. Asteroseismology studies from Hu et al. (2008), detecting differences in pulsation modes among various pulsating sdB stars, suggest progenitor intermediate-mass stars as a source of these non-canonical mass sdBs.

4 Conclusions

Given the wealth of information that asteroseismology methods can yield with regard to stellar parameters, such as the mass of a star, an ongoing study (such as that by *TESS*) of pulsating sdB stars promises to yield greater clarity about the evolutionary channels of sdB stars, including those in binary systems. To this end, more observations are needed. Brown and Boyle have studied the possibility of using the Specola Vaticana's VATT telescope on Mt. Graham in Arizona (USA) to study pulsating sdB stars. With photometry, the VATT's two CCD imagers can be used: 1) the VATT 4k CCD camera, or 2) the GUFI (Galway Ultra Fast Imager) L3CCD system, with a readout time of 2 ms and high time-resolutions of up to 400 images per second (subframed). A preliminary run has in fact been conducted using the 4k CCD camera, the hope being to achieve milli-mag pulsation resolution. The preliminary results are shown in the Figure below for PG 1047+003 (Fig. 1, right), as a test case in comparison with other observations already conducted by O'Donoghue et al. (1998). The sdB star PG 1419+081 has also been observed with the VATT. We coclude that much work needs to be done to achieve results.

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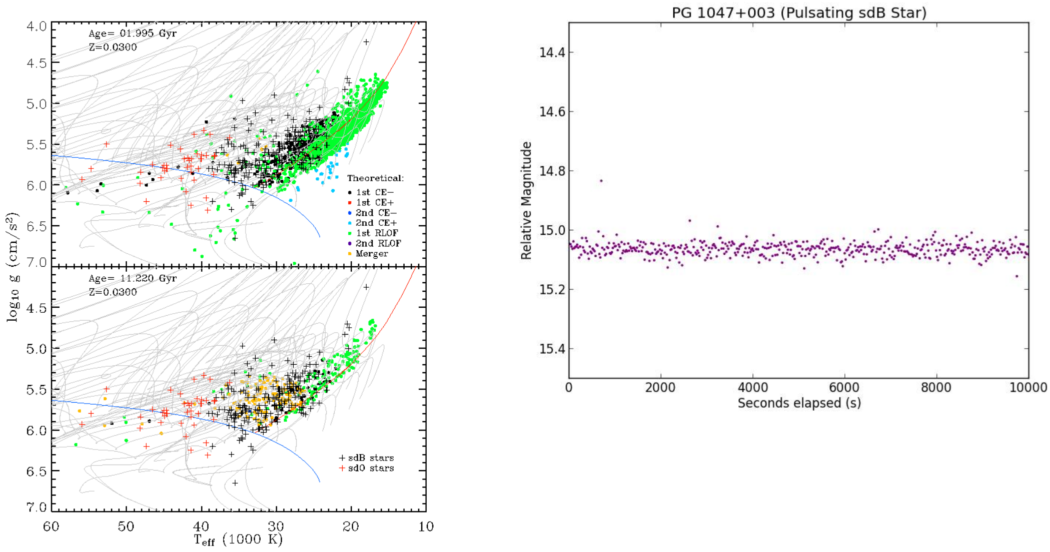

Fig. 1. Left: Shown above are Kiel diagrams for two ages (1.995 Gyr and 11.220 Gyr) for the $Z = 0.03$ SSP for which hot subdwarf stars appear below the ZAHeMS. Data from Saffer et al. (1994), Edelmann et al. (2003), Lisker et al. (2005), and Stroeer et al. (2007) are also plotted using the + symbols. EHB tracks (shown in grey) for core masses $0.35\,M_\odot$, $0.40\,M_\odot$, $0.45\,M_\odot$, $0.50\,M_\odot$, $0.55\,M_\odot$, $0.60\,M_\odot$, $0.65\,M_\odot$, $0.70\,M_\odot$, and $0.75\,M_\odot$ are shown going from right to left along the ZAHeMS, while for each core mass, the tracks for envelope masses of $0.00\,M_\odot$, $0.001\,M_\odot$, and $0.002\,M_\odot$, $0.005\,M_\odot$, $0.007\,M_\odot$, and $0.010\,M_\odot$ are shown going from bottom to top. **Right:** A preliminary sample of the light-curve obtained for PG 1047+003 from the VATT telescope.

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