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Letter to the Editor

Discovery of a helium-core white dwarf progenitor⋆,⋆⋆

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Abstract. We discovered that HD 188112, a bright ($V = 10\overset{\mathrm{m}}{.}2$), nearby (80 pc) B-type star, is a unique subluminous B (sdB) star. SdB stars are usually identified with models of core helium burning Extreme Horizontal-Branch (EHB) stars of half a solar mass. A spectral analysis of the hydrogen and helium lines resulted in $T_{\rm eff} = 21\,500 \pm 500$ K, $\log g = 5.66 \pm 0.05$ placing the star below the EHB. HD 188112 was found to be radial velocity (RV) variable and the RV curve has been measured to be perfectly sinusoidal with a period of 0.606585 days and a semi-amplitude of 188.3 $\mathrm{km\,s^{-1}}$ indicating that it is a close binary system. From the atmospheric parameters and the Hipparcos parallax we conclude that the sdB star is of low mass (0.24 $M_\odot$). The mass of the sdB is too low to sustain core helium burning and it is now evolving into a helium core white dwarf. A lower limit to the mass of its unseen companion of 0.73 $M_\odot$ is derived from the mass function. Because the companion does not contribute to the spectral energy distribution from the UV to the infrared it cannot be a main sequence star but must be a white dwarf (WD), a neutron star (NS) or a black hole. The system would qualify as pre-supernova Ia candidate (sdB+WD) if its total mass is above the Chandrasekhar limit (1.4 $M_\odot$), or as post-supernova (sdB+NS) if the companion mass is above that limit, requiring the inclination angle to be lower than 51° or 48°, respectively.

Key words. binaries: spectroscopic – stars: early-type – stars: fundamental parameters – stars: individual: HD 188112

1. Introduction

Most white dwarfs have C/O cores and a narrow mass distribution which peaks near 0.58 $M_\odot$ (e.g. Finley et al. 1997). However, a small population of low mass white dwarfs (<0.45 $M_\odot$) has been discovered (Finley et al. 1997). Since the canonical mass for the ignition of helium in the cores of red giants (helium flash) is 0.46 to 0.48 $M_\odot$, all white dwarfs with masses lower than that probably have helium cores. General consensus is that helium core white dwarfs must have formed by close binary evolution and Roche lobe overflow occurred before the red giant precursor reached the tip of the red giant branch (RGB). Indeed six low mass white dwarfs have been found to be radial velocity variable and therefore double degenerate systems (Marsh et al. 1995; Marsh 1995), the lowest white dwarf mass found up to now being 0.31 $M_\odot$.

A few white dwarfs have also been discovered as companions to neutron stars in milli-second pulsars and are found to be mostly helium white dwarfs with masses as low as ≈0.2 $M_\odot$ (Callanan et al. 1998). It is believed that these systems are endpoints of close binary evolution in which an old pulsar is spun-up by accretion from the secondary red giant (Bhattacharya & van den Heuvel 1991).

A class of stars closely related to the white dwarfs are subluminous B (sdB) stars. SdB stars are extreme Horizontal Branch (EHB) stars with low envelope masses (<0.01 $M_\odot$) which evolve directly to the white dwarf cooling sequence omitting the Asymptotic Giant Branch (AGB) phase (Heber 1986). There is growing evidence that the origin of sdB stars lies with close binary evolution since 2/3 of 40 sdB stars studied by Maxted et al. (2001) are found to be radial velocity variables with periods below 10h. Up to now periods have been determined for 38 radial velocity variable sdB stars (see Morales-Rueda et al. 2003 and references therein). The companions are either main sequence stars or white dwarfs. According to recent theoretical work (Han et al. 2002, 2003) sdB stars can form within binary systems either by common envelope ejection or by stable Roche lobe overflow. They can also be formed by the merger of two helium white dwarfs.

During our investigation of high resolution spectra of sdB stars to determine their metal abundances (Edelmann et al. 2001), we discovered that one of the brightest known sdB stars, HD 188112 ($V = 10\overset{\mathrm{m}}{.}2$), is radial velocity variable indicating that it is a binary system. Additional spectra taken in

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⋆ Based on observations collected at the German-Spanish Astronomical Center (DSAZ), Calar Alto, operated by the Max-Planck-Institut für Astronomie, Heidelberg jointly with the Spanish National Commission for Astronomy.

⋆⋆ Based on observations collected at the European Southern Observatory (ESO proposal No. 65.H-0341(A) and 69.D-0016(A)).

August 2002 allowed to determine the radial velocity curve, the atmospheric parameters and the mass.

2. Observations and spectral analysis

35 spectra were taken with the FEROS spectrograph at the ESO 1.5 m telescope. We used the standard setup (EEV CCD Chip with 2048 × 4096 pixel, pixel size of 15 μm, and entrance aperture of 2.7 arcsecs) resulting in a nominal resolution of $\lambda/\Delta\lambda$ = 48 000 covering 3600 Å to 8900 Å. The spectra were reduced using the on-line data reduction provided at ESO using the ESO-MIDAS program package.

Two high resolution spectra were also obtained at the Calar Alto 2.2 m telescope with the FOCES spectrograph. We used the Tektronic CCD Chip (1024 × 1024 pixel, pixel size of 24 μm, 200 μm entrance aperture and a slit width of 2 arcsecs), resulting in a nominal resolution of $\lambda/\Delta\lambda$ = 30 000 covering 3900 Å to 6900 Å. The spectra were reduced as described in Pfeiffer et al. (1998) using the IDL macros developed by the Munich group. Only two weak lines besides the strong Balmer lines, i.e. He I 5876 Å and Mg II 4481 Å, could be detected despite of the high resolution and high S/N of these spectra.

Low resolution spectra were obtained at the Calar Alto 3.5 m telescope with the twin spectrograph (spectral resolution 1.2 Å) and at the ESO Danish 1.5 m telescope with DFOSC (spectral resolution 4 Å).

The available high resolution spectra allow us to measure the radial velocity curve with excellent phase coverage and precision from the sharp NLTE core of the Hα line. The measurements are accurate to about ±1 km s^{-1}.

Since the system is single-lined the analysis is straightforward. A periodogram analysis was performed and the resulting power spectrum and the best fit RV curve are shown in Fig. 1. The period is P = 0.606585 ± 0.000002 d, the semi-amplitude K_1 = 188.3 ± 0.5 km s^{-1}and the systemic velocity γ_0 = 26.6 ± 0.3 km s^{-1}. Accordingly, the ephemeris for the time T_0 defined as the conjunction time at which the star moves from the blue side to the red side of the RV curve (cf. Fig. 1) is

$$\text{Hel. JD}(T_0) = 2\,452\,151.9359(3) + 0.606585(2) \times E.$$

From the period and semi-amplitude the mass function is derived: $f(m) = 0.4196 \pm 0.0033\,M_\odot$.

The Balmer line profiles measured from low resolution spectra were then analysed for $T_{\rm eff}$ and $\log g$ using LTE model atmospheres (Heber et al. 2000) and a χ^2 procedure described by Napiwotzki (1999). Thereafter the helium and magnesium abundances were determined by fitting the He I line (5876 Å) and the equivalent width of Mg II (4481 Å). The helium and magnesium abundances turned out to be remarkably low (He/H = 10^{-5} and Mg = 1/100 solar). The low magnesium abundance and the absence of other metal lines in the optical spectra indicate a low metal content and we adopted 1/100 solar for all metals.

Matching the synthetic Balmer line profiles to the three low resolution spectra available resulted in effective temperature $T_{\rm eff}$ = 21 500 ± 500 K, and gravity of $\log g$ = 5.66 ± 0.05. The result is insensitive to metallicity, e.g. increasing it to 1/10 solar reduces $T_{\rm eff}$ and $\log g$ insignificantly by 180 K and 0.02 dex.

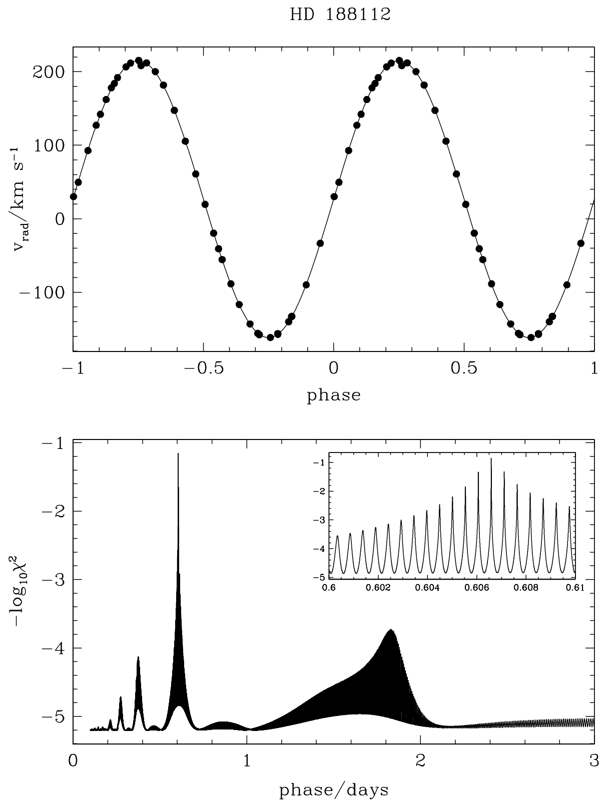

Fig. 1. Radial velocity curve and power spectrum of HD 188112.

Combining optical photometry (Kilkenny et al. 1998; Mermillod et al. 1997) with UV fluxes measured by the IUE satellite and NIR fluxes from the 2MASS catalog we can construct the spectral energy distribution (see Fig. 2). The latter is well matched by the sdB synthetic flux distribution calculated from the final model of the Balmer line analysis. As can be seen from Fig. 2, there is no evidence for light from the companion at any wavelength covered.

Combining the results of the spectroscopic analysis with a trigonometric distance measurement allows the direct determination of the mass of HD 188112. We derive the angular diameter by comparing the surface flux in the V band computed from the model atmosphere to the observed value. The HIPPARCOS satellite has measured a parallax of 12.33 ± 1.7 mas for HD 188112. Using the trigonometric distance we can derive the stellar radius, and from surface gravity and radius the mass results as $0.24^{+0.10}_{-0.07}\,M_\odot$. The error is dominated by the parallax error.

3. Evolutionary status

In order to discuss the evolutionary status of HD 188112 we compare the position of HD 188112 in the ($T_{\rm eff}$, $\log g$) diagram (Fig. 3) to that of other sdB stars in close binary systems for which periods have been determined (see Morales-Rueda et al. 2003). Also shown is the position of the Extreme Horizontal Branch and tracks for EHB and post-EHB evolution (Dorman et al. 1993). As can be seen from Fig. 3, HD 188112 lies below the zero age EHB whereas all other sdB stars lie more or less on the EHB band or above it. SdB stars lying above the

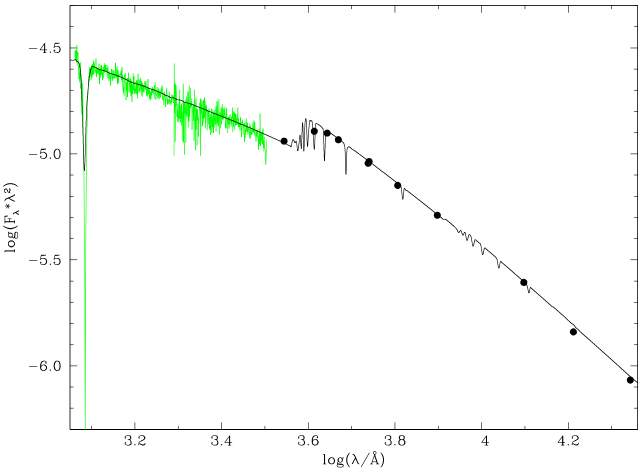

Fig. 2. Spectral energy distribution of HD 188112 compared to the synthetic spectrum calculated from the model which fits the Balmer lines best.

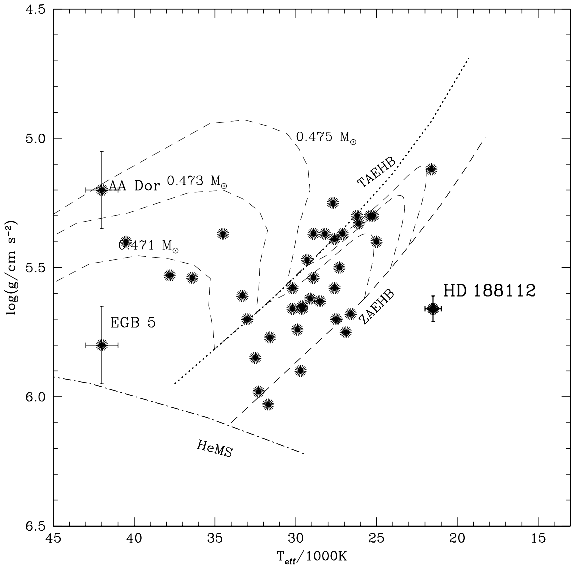

Fig. 3. Position of HD 188112 in the ($T_{\rm eff}$, log g) plane and comparison to sdB stars in close binary systems with known periods (Morales-Rueda et al. 2003) and evolutionary models for post-EHB evolution (Dorman et al. 1993).

EHB may have already exhausted their central helium fuel and therefore evolved off the EHB. The latter, however, does not hold for HD 188112 since the evolution of the EHB stars leads to increasing temperatures and lower gravities than observed for HD 188112 (see Fig. 3).

The channels by which sdB stars can form within a binary system have been studied by Han et al. (2002, 2003):
(i) The "common envelope (CE) ejection (CEE) channel" can be divided into two others. In the "first CEE channel", the initially more massive star experiences mass transfer when it is a red giant. This results in the formation of a CE, the spiraling in of both stars and consequently the ejection of the CE leading to the formation of a very close binary. If the core of the giant star still ignites helium it becomes a sdB. The final result is therefore a sdB star in a short period binary with a main sequence companion. In the "second CEE channel", the initially more massive star is already a white dwarf (WD).

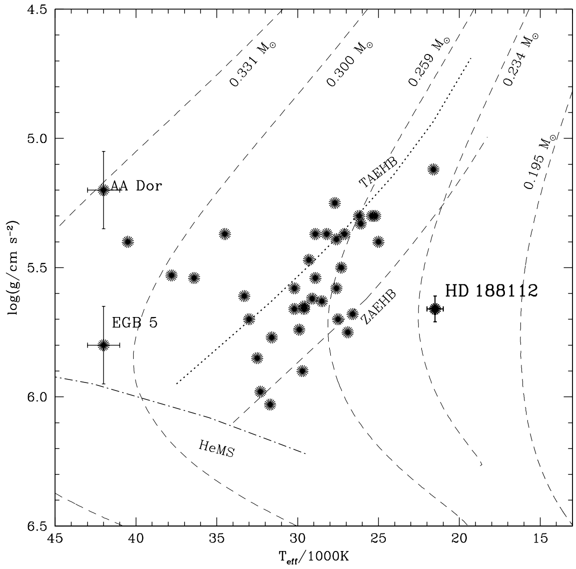

Fig. 4. Position of HD 188112 in the ($T_{\rm eff}$, log g) plane and comparison to sdB stars in close binary systems with known periods (Morales-Rueda et al. 2003) and models for post red giant branch evolution (Driebe et al. 1998).

(ii) The second channel is the "stable Roche lobe overflow (RLOF) channel" and involves stable mass transfer where a low-mass giant fills its Roche lobe on the red giant branch. The second RLOF channel (white dwarf companion) is found to be negligible for the sdB population.
(iii) The third channel is the "merger channel", i.e. sdB stars can be formed by the merger of two helium WDs if the mass is sufficient to burn helium in the core. Consequently the resulting sdB should be single.

The investigation of Han et al. (2003) also predicts a mass distribution for sdB stars peaked at the canonical sdB mass of 0.46 $M_\odot$ but much wider than assumed previously with masses ranging from 0.3 $M_\odot$ to 0.7 $M_\odot$. The highest masses are mostly mergers, while the lowest masses result from first stable Roche lobe overflow. Obviously the companions produced by the latter channel are main sequence stars. Since we can rule out a main sequence companion to HD 188112 (see below), the appropriate minimum mass, i.e. from common envelope ejection channels, is higher ($\approx$0.36 $M_\odot$, see Han et al. 2003).

The mass of HD 188112 as derived in Sect. 2 to be $M = 0.24^{+0.10}_{-0.07}\,M_\odot$ is far below the canonical sdB mass of 0.46 to 0.50 $M_\odot$ and also significantly below the lowest mass (0.36 $M_\odot$) predicted by the models of Han et al. (2003) as discussed above. It has most likely been formed via the second CEE channel The envelope probably has been removed before core helium burning began. The star will then evolve to become a helium core white dwarf. The evolution of such post-RGB stars has been calculated by Driebe et al. (1998) and evolutionary tracks for different masses are shown in Fig. 4. The position of HD 188112 in the ($T_{\rm eff}$, log g)-diagram is bracketed by the evolutionary tracks for $M = 0.195\,M_\odot$ and $M = 0.234\,M_\odot$; interpolation gives 0.23 $M_\odot$ in perfect agreement with the parallax based mass estimate (0.24 $M_\odot$). The mass range allowed by the tracks is extremely narrow (see Fig. 4). The evolutionary time since departure from the RGB is of the order 10^8 years according to the models of Driebe et al. (1998).

This indicates that HD 188112 is evolving into a helium core white dwarf with an unseen companion. A lower limit to the companion mass of $0.73\,M_{\odot}$ has been derived from the mass function. A main sequence star of such a mass would contribute significantly to the infrared flux distribution which is at variance with observations (see Fig. 2). Hence the companion cannot be a main sequence star but must be a compact degenerate object.

4. Discussion

In the spectral analysis presented above, HD 188112 was found to be a bona-fide progenitor of a helium core white dwarf. It is a binary consisting of sdB star with a mass of $0.24\,M_{\odot}$, too low to sustain core helium burning, and a compact object of at least $0.73\,M_{\odot}$, a white dwarf, neutron star or a black hole.

The mass of the sdB component is lower than observed for any known helium core white dwarf in white dwarf binaries. Such low mass white dwarfs, however, have been observed as companions to neutron stars (e.g. Callanan et al. 1998).

To the knowledge of the authors, only three other candidate progenitors to helium core white dwarfs in close binary systems are discussed in the literature, i.e. UX CVn (HZ 22, Schönberner 1978), AA Dor (LB 3459, Rauch 2000) and EGB 5 (Karl et al. 2003). Unlike HD 188112 these stars lie above and to the blue of the EHB in the ($T_{\rm eff}$, log g)-plane as can be seen from Fig. 3 for AA Dor and EGB 5. Their position can be matched by post-EHB or also by post-RGB tracks at masses somewhat higher than $0.3\,M_{\odot}$ (Fig. 4). Therefore their evolutionary status cannot be assigned.

The cases of HD 188112, AA Dor and EGB 5 indicate that it might be premature to assign a mass of $0.5\,M_{\odot}$ to a radial velocity variable sdB star as is often assumed (see also Han et al. 2003). However, the fraction of helium core sdB stars is likely to be small due to the short evolutionary time scale for post-RGB evolution to the sdB domain (10^7 yrs for the $0.259\,M_{\odot}$ model and 10^6 yrs for the $0.3\,M_{\odot}$ model of Driebe et al. 1998).

The mass of HD 188112 as derived from parallax and gravity ($0.24^{+0.10}_{-0.07}\,M_{\odot}$) is significantly below the limit for core helium burning stars formed through the second common envelope ejection phase ($0.36\,M_{\odot}$, Han et al. 2003). This mass estimate is also perfectly consistent with that from evolutionary tracks ($0.23\,M_{\odot}$). Therefore we regard HD 188112 as the most compelling case of a progenitor for a helium-core white dwarf. It is the brightest candidate and can be studied further in great detail. Since the system will merge due to loss of angular momentum by gravitational wave radiation, it would qualify as a pre-supernova Ia candidate (sdB+WD), if the total mass of the system is above the Chandrasekhar limit. This requires the inclination to be below $i = 51°$. If the companion mass is above $1.4\,M_{\odot}$ the companion could be a neutron star, in which case the inclination has to be below 48°. Hence HD 188112 could be a pre-SN Ia (sdB + massive WD) or a post-SN (sdB + neutron star/black hole) system.

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