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DISCOVERY OF A CLOSE SUBSTELLAR COMPANION TO THE HOT SUBDWARF STAR HD 149382—THE DECISIVE INFLUENCE OF SUBSTELLAR OBJECTS ON LATE STELLAR EVOLUTION

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ABSTRACT

Substellar objects, like planets and brown dwarfs orbiting stars, are by-products of the star formation process. The evolution of their host stars may have an enormous impact on these small companions. Vice versa a planet might also influence stellar evolution as has recently been argued. Here, we report the discovery of an 8–23 Jupiter-mass substellar object orbiting the hot subdwarf HD 149382 in 2.391 d at a distance of only about five solar radii. Obviously, the companion must have survived engulfment in the red giant envelope. Moreover, the substellar companion has triggered envelope ejection and enabled the sdB star to form. Hot subdwarf stars have been identified as the sources of the unexpected ultraviolet (UV) emission in elliptical galaxies, but the formation of these stars is not fully understood. Being the brightest star of its class, HD 149382 offers the best conditions to detect the substellar companion. Hence, undisclosed substellar companions offer a natural solution for the long-standing formation problem of apparently single hot subdwarf stars. Planets and brown dwarfs may therefore alter the evolution of old stellar populations and may also significantly affect the UV emission of elliptical galaxies.

Key words: binaries: spectroscopic – galaxies: evolution – planetary systems – stars: horizontal-branch – stars: individual (HD 149382) – stars: low-mass, brown dwarfs

1. INTRODUCTION

A long-standing problem in extragalactic astronomy is the ultraviolet (UV) excess observed in the spectra of elliptical galaxies. This phenomenon is caused by an old population of helium-burning stars, known as hot subdwarfs or sdBs (see review by Heber 2009). The origin of the UV excess can, hence, be traced back to that of the sdB stars themselves. The formation of such stars remains a mystery as it requires an extraordinarily high mass loss on the red giant branch. Hot subdwarfs often reside in close binaries, formed by ejection of the envelope of their red giant progenitors through interaction with the stellar companion. However, for half of the known sdBs no such companions could be found, requiring a yet unknown sdB formation channel.

After finishing core hydrogen burning, the progenitors of sdBs leave the main sequence and evolve to red giants before igniting helium and settling down on the extreme horizontal branch (EHB). Unlike normal stars, the sdB progenitors must have experienced a phase of extensive mass loss on the red giant branch, in order to explain the high temperatures and gravities observed at the surface of hot subdwarf stars. After consumption of the helium fuel, they evolve directly to white dwarfs avoiding a second red giant phase. What causes this extensive mass loss remains an open question.

The riddle of sdB formation is closely related to other long-standing problems regarding old stellar populations, which have been discussed for decades. The morphology of the horizontal branch in globular clusters, especially the existence and shape of its extreme hot part, is still far from understood (Catelan 2009). Hot subdwarfs are also regarded as the dominant source of the UV excess in early-type galaxies, where no active star formation is going on and hence no UV emission from young massive stars is expected. Hot subdwarf formation is the key to understanding the physics behind this phenomenon and a debate is going on whether single star (Yi 2008) or binary evolution (Han et al. 2007) explains the observed UV excesses.

About half of the sdB stars reside in close binaries with periods as short as ~ 0.1 d (Maxted et al. 2001; Napiwotzki et al. 2004a). Because the components' separation in these systems is much less than the size of the subdwarf progenitor in its red giant phase, these systems must have experienced a common-envelope and spiral-in phase (Han et al. 2002, 2003). In such a scenario, two main-sequence stars of different masses evolve in a binary system. The more massive one will first reach the red giant phase and at some point fill its Roche lobe, where mass is transferred from the giant to the companion star. When mass transfer is unstable, the envelope of the giant will engulf the companion star and form a common envelope. Due to friction with the envelope, the two stellar cores lose orbital energy and spiral toward each other until enough orbital energy has been deposited within the envelope to eject it. The end product is a much closer system containing the core of the giant, which then may become an sdB star, and a main-sequence companion. This companion evolves to a white dwarf after another phase of unstable mass transfer.

The common-envelope ejection channel provides a reasonable explanation for the extra mass loss required to form sdB stars. But for about half of all analyzed subdwarfs, there is no evidence for close stellar companions as no radial velocity (RV) variations are found. Although in some cases, main-sequence companions are visible in the spectra, it remains unclear whether these stars are close enough to have interacted with the sdB progenitors. Among other formation scenarios, the merger of two helium white dwarfs has often been suggested to explain the origin of single sdB stars (Han et al. 2002, 2003). Merging should result in rapidly spinning stars, which is not consistent with observations. A recent analysis of single sdB stars revealed that their $v_{\rm rot} \sin i$ distribution is consistent with a uniform rotational velocity $v_{\rm rot} \approx 8$ km s^{-1} and randomly oriented polar axes (Geier et al. 2009).

Table 1
Radial Velocities of HD 149382

Mid-HJD	RV (km s^{-1})	Instrument
2452497.49150	27.0 ± 0.2	FEROS
2452497.51327	26.9 ± 0.2	FEROS
2452497.56524	26.9 ± 0.2	FEROS
2452891.30690	25.3 ± 0.2	FOCES
2452892.30170	25.7 ± 0.9	FOCES
2452893.32160	23.9 ± 0.6	FOCES
2453784.83294	23.8 ± 0.2	UVES
2453904.73904	22.9 ± 0.2	FEROS
2453931.76614	26.8 ± 0.2	Coudé
2453932.71806	26.1 ± 0.2	Coudé
2453932.72485	25.7 ± 0.2	Coudé
2453932.74337	25.9 ± 0.2	Coudé
2453932.74882	25.7 ± 0.2	Coudé
2453932.84790	24.8 ± 0.2	Coudé
2453932.85560	25.1 ± 0.2	Coudé
2453986.54830	24.8 ± 0.2	FEROS

The planet discovered to orbit the sdB pulsator V 931 Peg with a period of 1170 d and a separation of 1.7 AU was the first planet found to have survived the red giant phase of its host star (Silvotti et al. 2007). Serendipitous discoveries of two substellar companions around the eclipsing sdB binary HW Vir at distances of 3.6 AU and 5.3 AU with orbital periods of 3321 d and 5767 d (Lee et al. 2009) and one brown dwarf around the similar system HS 0705 + 6700 with a period of 2610 d and a separation of less than 3.6 AU (Qian et al. 2009) followed recently. These substellar companions to hot subdwarfs have rather wide orbits, were not engulfed by the red giant progenitor and therefore could not have influenced the evolution of their host stars.

2. OBSERVATIONS AND ANALYSIS

HD 149382 is the brightest core helium-burning subdwarf known. The first hint that this star could show very small RV variations was found during our survey aimed at finding sdBs in long-period binaries (Edelmann et al. 2005). We obtained 15 high-resolution spectra ($R = 30{,}000$–$48{,}000$) within four years with three different high-resolution spectrographs (ESO-2.2 m/FEROS, McDonald-2.7 m/Coudé, CAHA-2.2 m/FOCES). One additional spectrum obtained with ESO-VLT/UVES at highest resolution ($R \approx 80{,}000$) was taken from the ESO archive.

In order to measure the RVs with highest possible accuracy, we fitted a set of mathematical functions (polynomial, Gaussian, and Lorentzian) to all suitable spectral lines with wavelengths from about 4000 Å to 6700 Å using the FITSB2 routine (Napiwotzki et al. 2004b). The formal deviation along the whole wavelength range was 0.2 km s^{-1} at best. In order to check the accuracy of this measurements, we also obtained RVs from telluric and night sky lines and reached similar accuracies. Since telluric and night sky lines have zero RV, we used them to correct the measured RVs for calibration errors. The applied corrections were usually below 1.0 km s^{-1}. Since we used four entirely different instruments and obtained consistent results other systematic effects should be negligible. The RV measurements are given in Table 1.

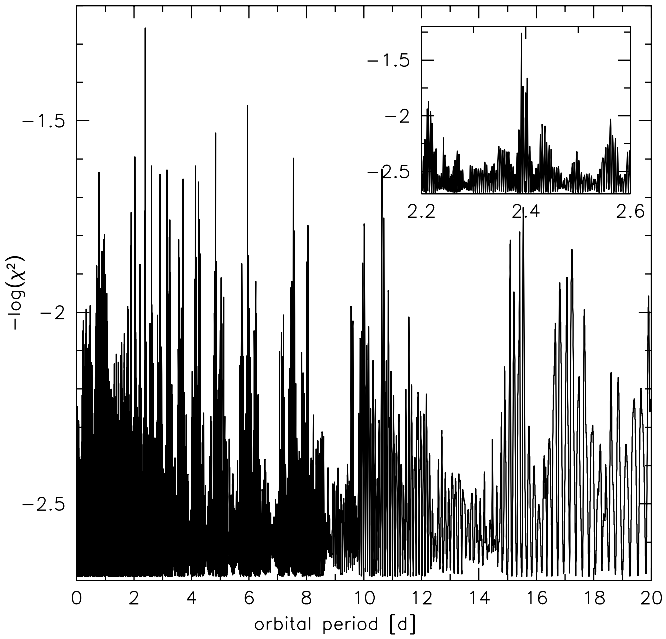

Figure 1. Power spectrum of HD 149382. − log χ^2 is plotted against the orbital period in days. The region around the most prominent period is plotted in the small window. The formal significance exceeds the 3σ-limit.

The period search was carried out by means of a periodogram based on the singular value decomposition (SVD) method. A sine-shaped RV curve was fitted to the observations for a multitude of phases, which were calculated as a function of period. The difference between the observed RVs and the best-fitting theoretical RV curve for each phase set was evaluated in terms of the logarithm of the sum of the squared residuals (χ^2) as a function of period. This method finally results in the power spectrum of the data set which allows to determine the most probable period P of variability (Lorenz et al. 1998). The formal significance of the best orbital solution ($P = 2.391 \pm 0.002$ d, $K = 2.3 \pm 0.1$ km s^{-1}, $\gamma = 25.3 \pm 0.06$ km s^{-1}) exceeds the 3σ-limit (see Figure 1) and a very small mass function $f(M) = 3.8 \times 10^{-6}$ results. The RV curve is shown in Figure 2. The formal probability that the next best alias periods at about 4.8 d and 6.0 d are correct is less than 5%. Even if one of these longer periods should be the correct one, the mass function increases only by a factor of 1.5 at most and our conclusions still remain valid.

The atmospheric parameters effective temperature $T_{\rm eff}$, surface gravity $\log g$, and helium abundance were determined by fitting simultaneously 17 hydrogen and helium lines in high-resolution, high-S/N FEROS and UVES spectra with NLTE model spectra (the method is described in Lisker et al. 2005; Geier et al. 2007). The parameters ($T_{\rm eff} = 35{,}500 \pm 500$ K, $\log g = 5.80 \pm 0.05$) are in good agreement with the result of Saffer et al. (1994): $T_{\rm eff} = 34{,}200 \pm 1500$ K, $\log g = 5.89 \pm 0.15$.

The mass of the unseen companion can be derived by solving the binary mass function $f_{\rm m} = M_{\rm comp}^3 \sin^3 i/(M_{\rm comp} + M_{\rm sdB})^2 = PK^3/2\pi G$. In order to obtain a unique solution, the mass of the sdB primary as well as the inclination of the system must be known. Due to the excellent quality of the data available for HD 149382, constraints can be put on both crucial parameters.

The distance to this star can be derived directly using a trigonometric parallax obtained with the *HIPPARCOS* satellite (van Leeuwen 2007). We derive the angular diameter by comparing the surface flux in the V band computed from a model atmosphere with the derived atmospheric parameters to the observed value (Mermilliod 1991). Using the trigonometric distance, we can derive the stellar radius, and from the surface gravity the mass of the sdB (Ramspeck et al. 2001).

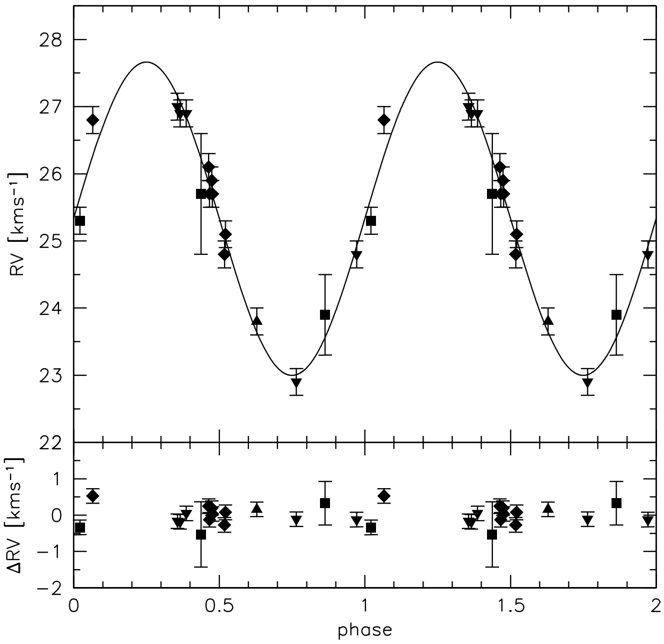

Figure 2. Radial velocity (RV) curve of HD 149382. The plot shows the RV plotted against orbital phase (diamonds: McDonald-2.7 m/Coudé, rectangles: CAHA-2.2 m/FOCES, upside down triangles: ESO-2.2 m/FEROS, triangle: ESO-VLT/UVES). The RV data were folded with the most likely orbital period. The residuals are plotted below.

Taking the uncertainties of all parameters into account (V magnitude, $T_{\rm eff}$, $\log g$, parallax), the possible mass range for the sdB is 0.29–0.53 $M_\odot$. This range is consistent with the canonical mass of 0.47 $M_\odot$ derived from single and binary evolution calculations (Han et al. 2002, 2003). Without further constraints on the inclination only a lower limit to the mass of the unseen companion can be calculated.

The minimum companion mass lies between 0.006 $M_\odot$ and 0.01 $M_\odot$, well below the stellar limit of 0.075–0.083 $M_\odot$ depending on the metallicity (Chabrier & Baraffe 1997), which is the lower limit where core hydrogen burning can be ignited and a star can be formed. The lower the inclination of the binary is, the higher is the mass of the unseen companion. Assuming a random distribution of orbital plane inclinations, the probability for a binary to fall below a certain inclination can be derived (Gray 1992). The probability for the companion to have a mass of more than 0.08 $M_\odot$ is just 0.8%. The probability that the mass of the unseen companion exceeds the planetary limit of 0.012 $M_\odot$ defined by the IAU[4] is only 33%.

However, we can constrain the mass of HD 149382 b even further. Due to the very high resolution of the UVES spectrum, the broadening caused by the projected rotational velocity of the star could be measured from the metal lines although it turned out to be as small as $v_{\rm rot}\sin i = 4.9 \pm 1.4$ km s^{-1}. In order to derive $v_{\rm rot}\sin i$, we compared the observed high-resolution ($R = 80{,}000$) UVES spectrum with rotationally broadened, synthetic line profiles. The profiles were computed using the LINFOR program (Lemke 1997). A simultaneous fit of elemental abundance, projected rotational velocity, and RV was then performed separately for every identified line using the FITSB2 routine (Napiwotzki et al. 2004b). The method is described in Geier et al. (2008).

Table 2

Parameters of the HD 149382 System

Trigonometric parallax[a]	π	(mas)	13.53 ± 1.15
Distance	d	(pc)	74^{+7}_{-8}
Visual magnitude[b]	$m_{\rm V}$	(mag)	8.947 ± 0.009
Atmospheric parameters			
Effective temperature	$T_{\rm eff}$	(K)	$35\,500 \pm 500$
Surface gravity	$\log g$		5.80 ± 0.05
Helium abundance	$\log y$		-1.44 ± 0.01
Projected rotational velocity	$v_{\rm rot}\sin i$	(km s^{-1})	4.9 ± 1.4
Orbital parameters			
Orbital period	P	(d)	2.391 ± 0.002
RV semiamplitude	K	(km s^{-1})	2.3 ± 0.1
System velocity	γ	(km s^{-1})	25.3 ± 0.06
Binary mass function	$f(M)$	($M_\odot$)	3.8×10^{-6}
Derived parameters			
Subdwarf mass	$M_{\rm sdB}$	($M_\odot$)	0.29–0.53
Orbital inclination	i	(°)	26–52
Companion mass	$M_{\rm comp}$	($M_{\rm J}$)	8–23
		($M_\odot$)	0.008–0.022
Separation	a	($R_\odot$)	5.0–6.1

Notes.

[a] The trigonometric parallax was taken from the new reduction of the *HIPPARCOS* data (van Leeuwen 2007).

[b] The visual magnitude is taken from Mermilliod (1991).

Assuming that HD 149382 rotates with the standard velocity of 8 km s^{-1} inferred for single sdBs (Geier et al. 2009), the inclination can be constrained to $i = 26°–52°$. The companion mass range is derived to be $M_2 = 0.008–0.022\,M_\odot = 8–23\,M_{\rm J}$ consistent with a gas giant planet or a low-mass brown dwarf. Adopting the statistically most likely inclination $i = 52°$ and the canonical sdB mass of 0.47 $M_\odot$ (Han et al. 2002, 2003), the companion mass is $0.011\,M_\odot = 12\,M_{\rm J}$, which places HD 149382 b just below the planetary limit. The separation of star and companion is 5–6 $R_\odot$. All relevant measurements and parameters of the HD 149382 system are summarized in Table 2.

3. DISCUSSION

When the progenitor of HD 149382 evolved through the red giant phase, it expanded to a radius of 10 times the present orbital separation. The initial separation must have been larger (about 1 AU) and the companion spiralled-in due to interaction with the giant's envelope until the envelope was ejected. Despite the very high local temperature inside the envelope (300,000–400, 000 K at 5–6 $R_\odot$ from the giant's center; Soker 1998), the substellar companion survived. The companion of the sdB star AA Dor has also been suggested to be a brown dwarf in a 0.26 d orbit (Rauch 2000; Rucinski 2009). This conclusion, however, is rendered uncertain as Vučković et al. (2008) derive a higher mass indicating that the companion is a star.

Soker (1998) suggested that substellar objects like brown dwarfs and planets may also be swallowed by their host star and that common-envelope ejection could form hot subdwarfs. Substellar objects with masses higher than $\approx 10\,M_{\rm J}$ were predicted to survive the common-envelope phase and end up in a close orbit around the stellar remnant, while planets with lower masses would entirely evaporate. The stellar remnant is predicted to lose most of its envelope and evolve toward the EHB. The orbital period and mass we derived for HD 149382 b are in excellent agreement with the predictions made by Soker

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[4] Position statement on the definition of a "planet." Working group on extrasolar planets of the International Astronomical Union, http://www.dtm.ciw.edu/boss/definition.html.

(1998). A similar scenario has been proposed to explain the formation of apparently single low-mass white dwarfs (Nelemans & Tauris 1998). The discovery of a brown dwarf with a mass of $0.053 \pm 0.006\,M_\odot$ in a 0.08 d orbit around such a white dwarf supports this scenario and shows that substellar companions can influence the outcome of stellar evolution (Maxted et al. 2006).

The discovery of planets and brown dwarfs around sdBs and especially the close-in substellar companion of HD 149382 may thus have important implications for the still open question of sdB formation. The extraordinary quality of the photometric data was a prerequisite for the detection of the substellar companions in V 931 Peg, HW Vir, and HS 0705 + 6700 (Silvotti et al. 2007; Lee et al. 2009; Qian et al. 2009). Finding such companions orbiting three of the best observed sdBs cannot be mere coincidence and leads to the conclusion that substellar objects may often be associated with sdBs. HD 149382 is the brightest sdB known. Hence, the quality of the spectroscopic data is also very high. It is not easy to detect such small RV variations even in high-resolution spectra. The fact that we found them in the case of HD 149382 leads to the conclusion that close-in planets or brown dwarfs may be common around apparently single sdB stars. They were just not detected up to now. Hence, all apparently single sdBs may have or had close brown dwarf or planetary companions, although those of lowest mass may have evaporated.

HD 149382 b provides evidence that substellar companions can decisively change the evolution of stars, as they trigger extensive mass loss. They could be responsible for the formation of the single hot subdwarf population. These stars are not only numerous in our Galaxy, but also make elliptical galaxies shine in UV light.

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