THE FAST-ROTATING, LOW-GRAVITY SUBDWARF B STAR EC 22081—1916: REMNANT OF A COMMON ENVELOPE MERGER EVENT

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Received 2011 March 18; accepted 2011 April 14; published 2011 May 3

ABSTRACT

Hot subdwarf B stars (sdBs) are evolved core helium-burning stars with very thin hydrogen envelopes. In order to form an sdB, the progenitor has to lose almost all of its hydrogen envelope right at the tip of the red-giant branch. In binary systems, mass transfer to the companion provides the extraordinary mass loss required for their formation. However, apparently single sdBs exist as well and their formation has been unclear for decades. The merger of helium white dwarfs (He-WDs) leading to an ignition of core helium burning or the merger of a helium core and a low-mass star during the common envelope phase have been proposed as processes leading to sdB formation. Here we report the discovery of EC 22081—1916 as a fast-rotating, single sdB star of low gravity. Its atmospheric parameters indicate that the hydrogen envelope must be unusually thick, which is at variance with the He-WD merger scenario, but consistent with a common envelope merger of a low-mass, possibly substellar object with a red-giant core.

Key words: stars: horizontal-branch – stars: individual (EC 22081—1916)

1. INTRODUCTION

Hot subdwarf B stars (sdBs) are evolved core helium-burning stars with very thin hydrogen envelopes residing at the extreme end of the blue horizontal branch (Heber 2009). The formation of these stars remains unclear. Normal horizontal branch stars are formed after core helium burning is ignited in the red-giant phase. Since the hydrogen envelopes of sdBs are extraordinarily thin, large mass loss is necessary right at the tip of the red-giant branch. In the case of the close binaries among the hot subdwarfs—about half of the known sdB stars are members of short-period ($P \lesssim 10$ days) systems (Maxted et al. 2001; Napiwotzki et al. 2004a)—the required mass loss is triggered by the formation of a common envelope, which is finally ejected. The formation of sdBs with main-sequence companions in wide orbits on the other hand can be explained by stable Roche lobe overflow (Han et al. 2002, 2003). The formation of single sdBs is less well understood. Several single star scenarios are currently under discussion (see Heber 2009, for a review), but all these scenarios require either a fine-tuning of parameters or extreme environmental conditions which are unlikely to be met for the bulk of the observed subdwarfs in the field. A particularly interesting scenario has been suggested by Soker (1998) and Nelemans & Tauris (1998): single sdB stars could be formed if a substellar companion in close orbit was engulfed by the red-giant progenitor and provided sufficient angular momentum to the common envelope before it was destroyed.

Alternative scenarios invoke stellar mergers to form single sdB stars. The merger of binary white dwarfs was investigated by Webbink (1984) as well as Iben & Tutukov (1984) who showed that an extreme horizontal branch (EHB) star can form when two helium core white dwarfs merge and the product is sufficiently massive to ignite helium. Politano et al. (2008) proposed the merger of a red-giant and a low-mass main-sequence star during the common envelope phase. However, the merger channel was under debate, because all single sdBs analyzed so far turned out to be slow rotators (Geier et al. 2009a), in contrast to the expectations. Here we report the discovery of the fast-rotating, single sdB EC 22081—1916.

2. OBSERVATIONS

EC 22081—1916 ($V = 12.9$ mag, $\delta_{2000} = 22^h10^m52^s9$, $\delta_{1916} = -19^\circ01'50''$) was discovered in the course of the Edinburgh-Cape blue object survey (Stobie et al. 1997) and classified as an sdB star by Copperwheat et al. (2011). Five high-resolution spectra were taken with the FEROS spectrograph ($R = 48,000, \lambda = 3750$–9200 Å) mounted at the ESO/MPG 2.2 m telescope at La Silla. The first spectrum was taken on 2006 June 14 followed by two exposures on August 9 and 11 in the same year. The last two spectra were taken consecutively on 2010 October 30. In total, the data points cover a timespan of 4.5 years. The spectra have been reduced with the FEROS-DRS pipeline in the context of the MIDAS package. A median filter was applied to correct for cosmics.

EC 22081—1916 has been monitored by planetary transit surveys. Due to its favorable declination it was observed by both the All Sky Automated Survey (ASAS; Pojmanski 1997) and the Northern Sky Variability Survey (NSVS; Woźniak et al. 2004). Both light curves have been downloaded from the data archives. The ASAS data set contains more than 450 data points of Johnson $V$ photometry. We selected data extracted with smallest aperture and included only measurements of sufficient quality (flagged from A to C). The light curve was folded to a period of 0.15 days (see Section 4) and binned. The white light curve from NSVS contains 93 data points and was phased in the same way. No variations exceeding 2% (NSVS) and 1% (ASAS) were detected.

The Vizier database contains several consistent proper motion measurements of this object. Among them the PPMXL ($\mu_\alpha \cos \delta = 17.0$ mas yr$^{-1}$, $\mu_\delta = -13.5$ mas yr$^{-1}$; Roessler et al. 2010) and UCAC3 ($\mu_\alpha \cos \delta = 17.7$ mas yr$^{-1}$, $\mu_\delta = -12.1$ mas yr$^{-1}$; Zacharias et al. 2010) values are independently measured and perfectly consistent within the error bars. Taking the average values we obtain $\mu = 21.6$ mas yr$^{-1}$.

3. ATMOSPHERIC PARAMETERS AND ROTATIONAL BROADENING

Atmospheric parameters and projected rotational velocity (see Table 1) have been determined simultaneously by fitting a
significant RV variations were measured. The RV of the star is
whereas the surface gravity log
abundance log
y
low for the effective temperature in question (see Figure 3).

From the spectral analysis to the Balmer and helium lines using
measured by fitting model spectra with fixed parameters derived
fit these lines, a very high rotational broadening of
vrot

added. Statistical errors are determined with a bootstrapping
algorithm.

metallicity LTE model atmospheres (Heber et al. 2000), to the
hydrogen Balmer lines (Hβ–H10) and helium lines (He i 4026,
4472, 4922, 5876 Å and He ii 4686 Å) using the SPAS routine
developed by H. Hirsch (e.g., Geier et al. 2011c). The single
spectra have been corrected for their orbital motion and co-
added. Statistical errors are determined with a bootstrapping
algorithm.

As can be seen in Figures 1 and 2, the Balmer line cores
and the helium lines are significantly broadened. In order to
fit these lines, a very high rotational broadening of
vrot
sin i = 163 ± 3 km s⁻¹ is necessary. The fact that no metal lines have
been found is consistent with this high broadening since weak
features melt into the continuum in this case. The resulting
effective temperature
Teff = 31,100 ± 1000 K and helium
abundance log y = −1.97 ± 0.02 are typical for sdB stars,
whereas the surface gravity of log g = 4.77 ± 0.10 is unusually
low for the effective temperature in question (see Figure 3).

The radial velocities (RVs) of the five single spectra were
measured by fitting model spectra with fixed parameters derived
from the spectral analysis to the Balmer and helium lines using
the FITSB2 routine (Napiwotzki et al. 2004b; see Table 1). No
significant RV variations were measured. The RV of the star is
constant at −13.1 ± 3.6 km s⁻¹.

By adopting the canonical mass of sdB stars (0.47 M⊙), we
can derive the distance from the atmospheric parameters and
the apparent magnitude following Ramspeck et al. (2001). The
transversal velocity
vi
of the star in km s⁻¹ can then be calculated
using the simple formula
vi = 4.74 dμ, where the distance
is given in kpc and the proper motion μ in mas. The distance to
the star is ≃1.5 kpc and the transversal velocity ≃150 km s⁻¹
perfectly consistent with an evolved star in the thick disk or in
the halo (e.g., Tillich et al. 2011).

4. CONSTRAINTING THE NATURE OF EC 22081−1916

EC 22081−1916 has the highest
vrot
sin i ever measured for
an sdB star. All other single sdB stars analyzed so far have
vrot
sin i < 10 km s⁻¹ (Geier et al. 2009a). In the following,
we discuss and exclude several possible explanations for this
finding.

Main-sequence star? Rotational velocities exceeding
100 km s⁻¹ are quite common among main-sequence A and B
stars. Since the surface gravity log g = 4.77 is at the lower end
of the hot subdwarf parameter range, the star may be regarded
as a misclassified massive main-sequence star. This inter-
pretation, however, can be ruled out because the surface gravity
is too high (see Figure 3) and the helium abundance (1/10-
solar) far too low. A double-lined binary consisting of two hot

| mid-HJD     | RV     | Teff  | log g | log y | vrot sin i |
|------------|--------|-------|-------|-------|------------|
| 2453900.845477 | −11.0 ± 1.0 | 31,500 ± 150 | 4.74 ± 0.02 | −1.91 ± 0.03 | 172 ± 4.0 |
| 2453956.793848a | −18.6 ± 2.6 | ⋯ | ⋯ | ⋯ | ⋯ |
| 2453958.634893 | −13.4 ± 1.3 | 31,500 ± 190 | 4.81 ± 0.03 | −1.83 ± 0.04 | 150 ± 5.0 |
| 2454599.620294 | −13.6 ± 1.0 | 29,800 ± 140 | 4.67 ± 0.02 | −2.01 ± 0.03 | 172 ± 4.0 |
| 2455499.639508 | −9.0 ± 1.0 | 31,200 ± 170 | 4.83 ± 0.03 | −1.90 ± 0.04 | 170 ± 4.0 |
| Co-added     | 31,100 ± 100 | 4.77 ± 0.02 | −1.97 ± 0.02 | 163 ± 3.0 | |

Note. a Spectrum with low signal-to-noise ratio.

Figure 1. Fit of synthetic LTE models to some hydrogen Balmer lines. The thin
solid line marks models without rotational broadening, the thick solid line the
best fitting model spectrum with
vrot
sin i = 163 km s⁻¹.

Figure 2. Fit of synthetic LTE models to helium lines (see Figure 1). The
extreme rotational broadening of the lines is obvious.
main-sequence stars is another option. An unresolved, double-lined binary may explain the high measured surface gravity, which could be overestimated in this case. However, we cannot imagine a combination of main-sequence stars that would produce such an unusual spectrum.

**Hot subdwarf with unresolved pulsations?** Two kinds of sdB pulsators are known. The slow pulsations of the V 1093 Her stars (sdBV), are not expected to influence the line broadening significantly. In the case of the short-period pulsators (V 361 Hya type, sdBV), unresolved pulsations can severely affect the broadening of the lines and therefore mimic higher projected rotational velocities (\(v_{\text{rot}} \sin i\)). Telting et al. (2008) showed that this happens in the case of the hybrid pulsator Balloon 09010001. Unresolved pulsations are also most likely responsible for the high measured projected rotational velocity of EC 22081–1916. The colors and internal temperatures of EC 22081–1916 are consistent with the ones of short-period pulsating sdBs. The typical pulsation periods of sdBV stars are of the order of a few minutes and therefore shorter than the exposure times. However, the measured \(v_{\text{rot}} \sin i = 163 \text{ km s}^{-1}\) is so high that very large photometric variations at periods of a few minutes would be inevitable. Therefore, the broadening cannot be caused by unresolved pulsations. The prominent mode of the strongest known sdB pulsator PG 1605+072 has a photometric amplitude of \(\sim 13\%\) (Koen et al. 1998) and an RV amplitude of \(\sim 15 \text{ km s}^{-1}\) (O’Toole et al. 2005b). In order to cause the line broadening necessary to fit EC 22081–1916, both values would have to be much higher. Due to the fact that we neither detect RV variations nor any features in the light curves (see Figure 4) we conclude that EC 22081–1916 is not a high-amplitude pulsator.

**Hot subdwarf with high magnetic fields?** O’Toole et al. (2005a) discovered magnetic fields up to \(\sim 1.5\) kG in a small sample of sdB stars. From the analysis of magnetic white dwarfs with field strengths in the MG range, it is known that small Zeeman splitting can mimic a broadening of the spectral lines (see, e.g., Külebi et al. 2009). Could EC 22081–1916 be the prototype of a new sdB class with very strong magnetic fields? Looking at Figures 1 and 2, this explanation can be ruled out as well. Zeeman splitting affects every single spectral line in a different way. In contrast to that, the broadening of the lines is uniform. We therefore conclude that the line broadening of EC 22081–1916 is caused by rotation.

**Close binary with large RV amplitude and orbital smearing?** The hot subdwarfs with the highest measured projected rotational velocities (\(v_{\text{rot}} \sin i > 100 \text{ km s}^{-1}\)) all reside in very close binary systems with orbital periods of \(\sim 0.1\) days. These sdBs were spun up by the tidal influence of their close companions and their rotation became synchronized to their orbital motion (Geier et al. 2007, 2010).

A close companion would therefore be the most natural explanation for the high measured projected rotational velocity of EC 22081–1916. The colors of this star (\(J - K_S \approx 0.0, 2\text{MASS}; \text{Skrutskie} \text{et al.} \text{2006}\)) do not show any signs of a cool companion (Stark & Wade 2003). A possible unseen companion must therefore be either a low-mass main-sequence star, a compact object like a white dwarf, or a substellar object.

White dwarf and main-sequence companions can be immediately ruled out because no significant RV variations are detected on timescales of years, days, and half an hour. This is also a strong argument against the hypothesis that the strong line broadening may be at least partly caused by orbital smearing. Since the exposure times of the FEROS spectra are rather long.
(900–1500 s), the RV shift during the exposure would be large in a close binary with high RV amplitude (e.g., Geier et al. 2007). However, no RV variations are measured (see Figure 4, upper panel). Furthermore, a quantitative spectral analysis as outlined in Section 3 has been performed for a single FEROS spectrum and no significant variations in the atmospheric parameters or the \( v \text{rot} \sin i \) were detected (see Table 1). Orbital smearing can therefore be ruled out.

**Close binary with small RV amplitude?** The remaining option would be a substellar companion in a very close orbit similar to the sdB+brown dwarf (BD) binary SDSS J08205+0008 (Geier et al. 2011b). Assuming that the rotation of EC 22081–1916 is synchronized, an upper limit for the orbital period can be calculated. Adopting \( M_{\text{sdB}} = 0.47 M_\odot \) and using the measured \( \log g \), the radius of the star is \( R_{\text{sdB}} = \sqrt{M_{\text{sdB}} G / \rho} \simeq 0.47 R_\odot \). Taking the inclination into account (\( v_{\text{rot}} \geq v_{\text{rot}} \sin i \)), we can calculate an upper limit for the orbital period \( P \leq 2\pi R_{\text{sdB}} / v_{\text{rot}} \sin i \simeq 0.145 \) days. Another strict constraint is set by the lack of significant RV variations. Taking the standard deviation of the RV measurements and multiplying it by 3 we end up with a conservative upper limit for the RV semi-amplitude \( K < 12 \text{ km s}^{-1} \).

Adopting the upper limits for \( P \) and \( K \), the companion would have to be a brown dwarf with \( P \simeq 0.1 \text{ days} \) and a radius of \( K \simeq 0.1 R_\odot \). For inclinations lower than 90° the orbital period of the putative binary must be shorter, because the absolute rotational velocity of the sdB has to be higher to keep \( v_{\text{rot}} \sin i \) fixed at the observed value.

However, other important constraints have to be met as well. Neither the sdB nor its putative companion is allowed to fill their Roche lobes, because in this case the system would exchange mass. Since no indicative features for ongoing mass transfer (e.g., emission lines) are present in the spectra, the system must be detached. Calculating the Roche radii of both components as outlined in Eggleton (1983) we derive a minimum orbital period for the system of \( \geq 0.11 \) days and a minimum inclination of 47°. For shorter periods and hence lower inclinations the sdB would fill its Roche lobe. A similar limit (\( \geq 0.1 \) days) is derived, if we allow \( K \) to be smaller than \( 12 \text{ km s}^{-1} \). For orbital periods shorter than that, a putative brown dwarf companion would fill its Roche lobe.

These simple calculations show that the possible parameter space of a close and synchronized binary would be extremely narrow (\( P \simeq 0.1–0.15 \) days, \( K \simeq 4–12 \text{ km s}^{-1} \)). Furthermore, all possible configurations would lead to photometric variabilities easily visible in the light curve. Close sdB+dM or BD systems are not only often eclipsing, but also show sinusoidal variations due to light from the irradiated surface of the cool companion (e.g., Østensen et al. 2010; For et al. 2010; Geier et al. 2011b). Due to its high temperature and low surface gravity EC 22081–1916 has a very high luminosity compared with other sdBs, which should lead to a very strong reflection effect at inclinations of \( \geq 50° \) or higher. Since no variations were found in the ASAS and NSVS light curves (Figure 4), a nearby low-mass companion can be excluded as well.

**5. CONCLUSION**

After excluding all possible alternative scenarios we conclude that EC 22081–1916 is the first single sdB star which is rapidly rotating. Furthermore, the \( \log g \) of EC 22081–1916 is the lowest one ever measured for an sdB (see Figure 3). Østensen et al. (2011) argued that the low gravity of the pulsating sdB J20163+0928 (\( \log g = 5.15 \)) may be due to a rather thick layer of hydrogen. In the model of Han et al. (2002, 2003) even the merger remnants with the highest masses would need a hydrogen layer of \( \leq 0.01 M_\odot \) to reach at such low surface gravities.

The formation of such an object through single star evolution is very hard to explain. EC 22081–1916 thus might have been formed by a merger event. Three merger scenarios have been proposed to explain the origin of hot subdwarfs. Webbink (1984) and Iben & Tutukov (1984) proposed the merger of two He-WDs as possible formation channel, which has been further explored by Saio & Jeffery (2002). Han et al. (2002, 2003) included this channel in their binary evolution calculations and were able to model both the UV excess in elliptical galaxies (Han et al. 2007) and the different close binary fractions of sdBs in populations of different age in a consistent way (Han 2008). He-WD mergers are believed to have very small envelope masses and are expected to be situated at the very blue end of the EHB. Both are at variance with the position of EC 22081–1916 in the \( T_{\text{eff}}–\log g \) diagram (see Figure 3). Justham et al. (2010) proposed that the merger of a close binary system consisting of an sdB and an He-WD may form a single helium-enriched sdO. EC 22081–1916, however, is helium deficient.

EC 22081–1916 most likely belongs to an old stellar population, either thick disk or halo. Its position in the \( T_{\text{eff}}–\log g \) diagram (see Figure 3) may indicate a mass higher than canonical, which would be consistent with the predictions by Han et al. (2002, 2003). If it should be the remnant of an He-WD merger, this would imply important constraints on the merger process itself. Since the helium abundance of EC 22081–1916 is 10 times below the solar value, enough hydrogen must have survived the merger and must have been enriched in the atmosphere by diffusion processes.

The third channel was suggested by Soker (1998) and further explored by Soker & Harpaz (2000, 2007). Politano et al. (2008) followed this idea and focused on the formation of hot subdwarfs. The merger of a red-giant core and a low-mass, main-sequence star or substellar object during a common envelope phase may lead to the formation of a rapidly rotating hot subdwarf star. This scenario fits particularly well with observations for several reasons.

First, the helium core of a red giant merges with an unevolved low-mass star or a brown dwarf. Both have hydrogen-rich envelopes. This provides a natural explanation for the low He abundance and surface gravity of the remnant. The hydrogen is provided by the merged companion. Furthermore, this companion also provides the energy required to eject the envelope and form the sdB. Several sdBs with low-mass stellar and substellar companions have been found most recently and the true number may be much higher due to selection effects (e.g., For et al. 2010; Østensen et al. 2010; Geier et al. 2009b, 2011a, 2011b).

A very important prediction made by Politano et al. (2008) is that sdBs formed via the CE-merger channel should be rare. EC 22081–1916 is unique among \( \simeq 100 \) slowly rotating sdB stars analyzed so far (Geier et al. 2009a). In contrast to that, Han et al. (2002, 2003) predict a large fraction if not all of the single sdBs to be formed by WD mergers. Unless there is a mechanism to get rid of all the angular momentum involved in a merger as suggested by Saio & Jeffery (2002), this observation is hard to explain.

Furthermore, Politano et al. (2008) predict that a large fraction of the sdBs formed after CE merger should rotate with a critical velocity \( v_{\text{crit}} \), which is defined as the rotational velocity at which mass loss induced by centrifugal forces prevents the red-giant core to accrete more material from the secondary. Politano
et al. (2008) estimate this critical velocity to be about one-third of the breakup velocity \( v_{br} = (GM/R)^{1/2} \). Using the parameters derived for EC 22081−1916, we calculate \( v_{crit} \approx 145 \text{ km s}^{-1} \) perfectly consistent with the projected rotational velocity measured from the spectrum.

In conclusion, the scenario proposed by Soker (1998) and Politano et al. (2008) fits best with the observational data obtained so far, although the He-WD+He-WD or sdB+He-WD merger scenarios cannot be ruled out. EC 22081−1916 is the first candidate for a merger remnant among the hot subdwarf stars. Similar objects are expected to be found in large spectroscopic databases like Sloan Digital Sky Survey (SDSS). Due to the high rotational broadening, the quality of these data should be sufficient to find them.

Based on observations at the La Silla Observatory of the European Southern Observatory for program numbers 082.D-0649 and 084.D-0348. S.G. is supported by the Deutsche Forschungsgemeinschaft (DFG) through grant HE1356/49-1. We thank L. Morales-Rueda for sharing her data with us. Furthermore, S.G. wants to thank Ph. Podsiadlowski, C. S. Jeffery, R. H. Østensen, and S. J. O‘Toole for discussing and partly defending the merger channel as a possible formation scenario for hot subdwarfs. Special thanks go to the organizers of the 4th sdOB meeting in Shanghai where these and other problems were discussed.

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