Hot subluminous stars: Highlights from the MUCHFUSS and *Kepler* missions

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Abstract. Research into hot subdwarf stars is progressing rapidly. We present recent important discoveries. First we review the knowledge about magnetic fields in hot subdwarfs and highlight the first detection of a highly-magnetic, helium-rich sdO star. We briefly summarize recent discoveries based on *Kepler* light curves and finally introduce the closest known sdB+WD binary discovered by the MUCHFUSS project and discuss its relevance as a progenitor of a double-detonation type Ia supernova.

1. INTRODUCTION

Subdwarf stars of spectral type O and B (sdO, sdB) are core helium-burning stars at the hot end of the horizontal branch (the extreme horizontal brach, EHB) or have evolved even beyond that stage. About half of the sdBs reside in close binaries; companions are white dwarfs or low-mass main-sequence stars. Binary population-synthesis models explain naturally the actual sdB binary fractions if white-dwarf mergers are considered as well. Research into hot subdwarf stars is a florishing field because the wide variety of phenomena observed in such stars can be used to tackle important issues in modern astrophysics, ranging from the fate of planets around evolved stars to the progenitors of type Ia supernovae and the origin of the UV excess in early-type galaxies. A review of the field has been done by [1], while the crucial issue of hot subdwarf formation is reviewed in these proceedings by [2]. A more recent census can be found in the proceedings of the *Fifth Meeting on Hot Subdwarf Stars and Related Objects* [3]. Here we highlight some important recent discoveries. First we address the issue of magnetic fields of hot subdwarf stars, because major progress has been achieved in 2012. As for many other fields of astrophysics, the *Kepler* mission has a great impact on the development of the research field of hot subdwarfs by providing light curves of pulsating sdB stars and close sdB binaries. We shall give examples in Section 3. Finally, we shall introduce the MUCHFUSS project and present the most recent discoveries including CD−30°11223, a candidate supernova Ia progenitor system.

2. A MAGNETIC SUBDWARF O STAR

Attempts to detect magnetic fields in hot subdwarf stars up to now met with little success. Only a little more than half a dozen stars [4–7] have been studied up to 2011 and the detection of kG-fields has been reported. More extensive studies have become available recently [8–10] covering 41 hot subdwarfs. [10] carried out a critical reinvestigation of published data from the FORS1 instrument at the ESO/VLT and new observations. Not a field with standard errors of the order of 200–400 G could be found. Previous

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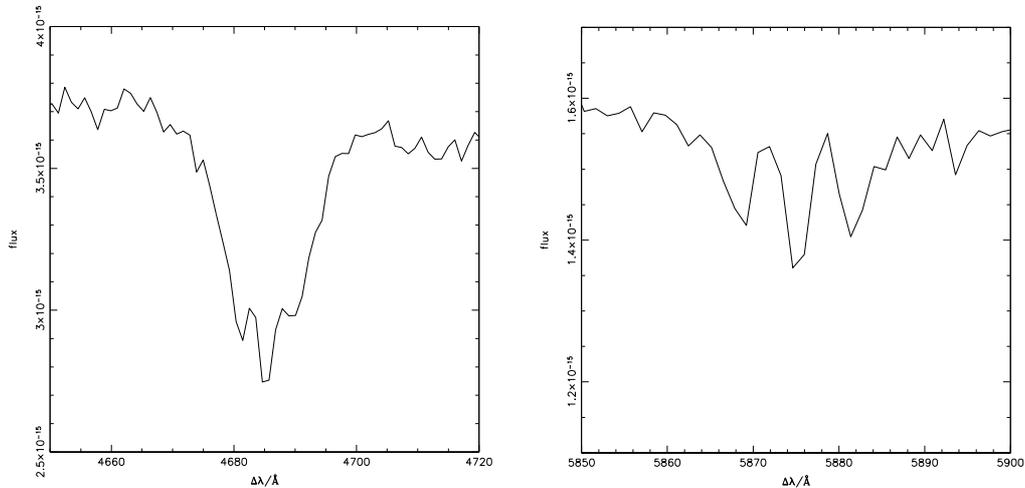[a]e-mail: `ulrich.heber@sternwarte.uni-erlangen.de`

Figure 1. Spectral lines of ionized (4686Å, left panel) and neutral helium (5875Å, right panel). The Zeeman splitting into three components is obvious, indicating a magnetic field strength of ≈ 300–$700\,$kG.

claims based on VLT-FORS data were found to be invalid because of wavelength calibration problems. [10] conclude that "there is presently no strong evidence for the occurrence of a magnetic field in any sdB or sdO star, with typical longitudinal field uncertainties of the order of 2–400 G. It appears that globally simple fields of more than about 1 or 2 kG in strength occur in at most a few percent of hot subdwarfs." Therefore it was somehow a surprise when a helium-rich sdO star was recently discovered to show Zeeman splitting ([11], see Fig. 1), indicating the presence of a $\approx$300–700 kG magnetic field.

Most magnetic white dwarfs are of spectral type DA, that is hydrogen-rich. The newly discovered magnetic sdO star, however, is helium-rich and therefore will probably evolve into a DB white dwarf, that is also helium rich. However, highly magnetic DBs are rare compared to magnetic DAs. Hence, we should expect to find many more highly magnetic hot subdwarfs, which still need to be discovered.

3. HOT SUBDWARF STARS IN THE *KEPLER* FIELD

The *Kepler* mission provided light curves of unprecedented precision for hot subdwarf stars. The initial interest of sdB stars in the *Kepler* field was to study their oscillations [12]. Two classes of such multi-mode, low-amplitude pulsators are known: the short-period V361 Hya stars (P≈120–600 s) and the V1093 Her stars (P $\approx$ 45–120 min). The former are g-mode while the latter are p-mode pulsators. Both classes of pulsators are separated in the Hertzsprung-Russell Diagram (HRD): V361 Hya stars are hotter than 28000 K while all V1093 Her stars have temperatures below that limit. A few so-called hybrid pulsators are found near this temperature. A long-standing puzzle is that the fraction of sdB stars in the (hotter) V361 Hya instability strip is very small while most of the sdBs in the (cooler) V1093 Her instability strip do pulsate. It was anticipated that the high precision and long duration of the *Kepler* light curves would allow to detect pulsations in many more sdB stars at photometric amplitudes lower than can be obtained from the ground.

During the first year of the *Kepler* mission, thirty-two sdB pulsator candidates hotter than 28 000 K have been surveyed [12] and only one was found to be an unambiguous V361 Hya pulsator. Amongst the sixteen sdB stars cooler than 28 000 K in the *Kepler* sample, twelve stars (75%) showed V1093 Her type pulsation, the fraction being in agreement with expectations from ground-based studies. [12] conclude that "thanks to the exceptional precision of the *Kepler* measurements, we can now conclude that there certainly are sdB stars, both on the hot and on the cold ends of the EHB, that show no trace of pulsations.

Possible explanations for the non-pulsators would have to answer why the pulsation driving mechanism is suppressed in some EHB stars and not in other."

Besides pulsating stars, some sdB+WD binaries were found in the *Kepler* sample. In addition to ellipsoidal variations caused by tidal distortions of the sdB star, the *Kepler* light curves show variations caused by Doppler boosting. This allows to determine the semi-amplitude of the radial velocity (RV) from the light curve alone. A particularly impressive case is provided by the eclipsing binary KPD 1946+4340. A photometric radial velocity amplitude of $168 \pm 4 \, \mathrm{km \, s^{-1}}$ in excellent agreement with the spectroscopic one of $K = 164.0 \pm 1.9 \, \mathrm{km \, s^{-1}}$ was derived [13]. Even gravitational lensing has to be taken into account, because it is found to affect the depth of the eclipse at orbital phase 0.5. The analysis of radial velocity and *Kepler* light curves allowed [13] to derive the masses of both the sdB and the white dwarf. The mass of the sdB, $0.47 \pm 0.03 \, M_{\odot}$, is very close to the canonical EHB mass and to the predictions by population synthesis models [14]. The mass of the companion, $0.59 \pm 0.02 \, M_{\odot}$, is typical for C/O white dwarfs.

4. MUCHFUSS

The project *Massive Unseen Companions to Hot Faint Underluminous Stars from SDSS (MUCHFUSS)* aims at finding hot subdwarf binaries with massive companions through optical spectroscopic and photometry [15]. The SDSS spectroscopic database is the starting point of that survey. Hot subdwarf candidates were selected by applying a color cut to SDSS photometry. All point source spectra with colors $u - g < 0.4$ and $g - r < 0.1$ were selected and downloaded from the SDSS Data Archive Server[1]. By visual inspection, around 10 000 hot stars were selected and classified. The sample contains 1369 hot subdwarfs. Subdwarf B stars with radial velocities lower than $\sim 100 \, \mathrm{km \, s^{-1}}$ were rejected to filter out such binaries with normal disc kinematics, by far the majority of the sample. Another selection criterion is the brightness of the stars: most objects fainter than $g \approx 19$ mag have been excluded.

However, it turns out that the MUCHFUSS selection strategy also allows to detect low-mass companions of sdBs in very close orbits. Two eclipsing sdB binaries with brown dwarf companions were found in the course of the MUCHFUSS photometric follow-up campaign [16, 17] and are discussed in the next subsection, while the shortest period sdB+WD system from MUCHFUSS is highlighted in section 4.2.

4.1 Subdwarf B plus brown dwarf systems

Subdwarf B stars with low mass, non-degenerate companions are named after the prototype HW Vir stars, if they are eclipsing. Such objects are rare. The MUCHFUSS project has discovered two such systems via photometry at the Mercator telescope and the CAHA-2.2m telescope equipped with BUSCA. The mass of the companion in eclipsing sdB binary J082053.53+000843.4, $0.045 - 0.068 \, M_{\odot}$, turned out to be lower than the hydrogen-burning limit ($0.07 - 0.08 \, M_{\odot}$ depending on metallicity). Hence this HW Vir system hosts a brown dwarf companion [15].

Very recently a similar HW Vir system, J162256.66+473051.1, was discovered in the course of the MUCHFUSS project ([17], see Fig. 2). Its orbital period is as short as $\simeq 0.07$ d but the RV semi-amplitude is quite low ($\simeq 47 \, \mathrm{km \, s^{-1}}$). Although the analysis is still ongoing, it appears likely that the companion is substellar as well.

The success of MUCHFUSS in the finding of low-mass companions illustrates that its target selection not only singles out sdB binaries with massive companions and therefore high RV-amplitudes, but also low mass systems with very short orbital periods. These results add to the growing evidence
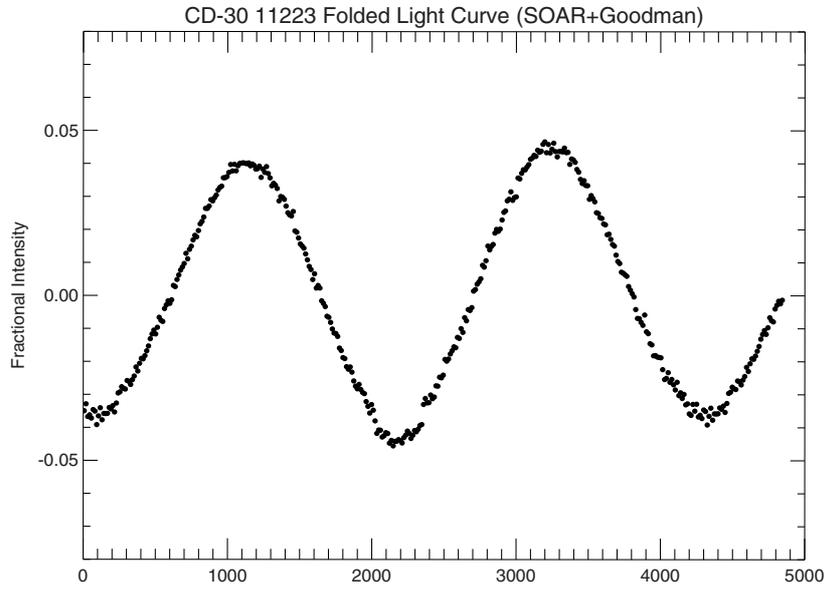
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Figure 2. Phased light curves of J162256.66+473051.1 taken with BUSCA (UV, B, R, IR-band). Primary and secondary eclipses are clearly observed as well as the sinusoidal shape caused by the reflection effect (from [17]).
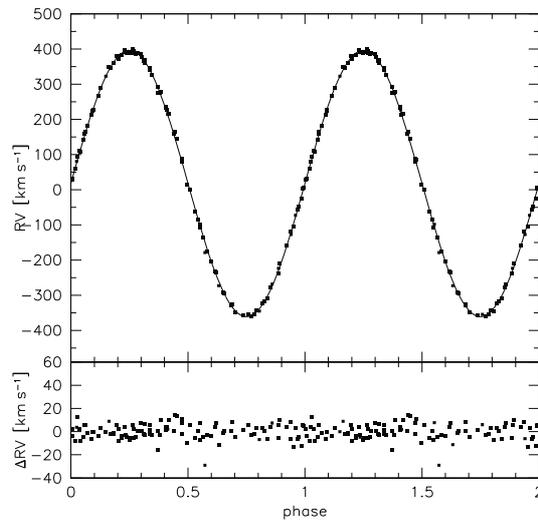

Figure 3. Radial velocity curve of $CD-30°11223$ derived from 105 spectra taken with WHT/ISIS (from [20]).

that low-mass stellar and substellar companions may play an important role in the formation of sdB stars (e.g. [18]).

4.2 $CD-30°11223$

$CD-30°11223$ is an sdB star recently discovered amongst blue stars in the GALEX survey [19]. The star was chosen as a bright backup target for our MUCHFUSS follow-up campaign. Due to bad

Table 1. Parameters of the CD−30°11223 system.

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Distance	d	[pc]	290 ± 50
Visual magnitude*	m_V	[mag]	11.90 ± 0.18
Effective temperature	T_{eff}	[K]	$29\,200 \pm 400$
Surface gravity	$\log g$		5.66 ± 0.05
Helium abundance	$\log y$		-1.50 ± 0.07
Projected rotational velocity	$v_{rot} \sin i$	[km s^{-1}]	177 ± 10
Orbital period	P	[d]	$0.0489790717 \pm 0.0000000038$
RV semi-amplitude	K	[km s^{-1}]	376.6 ± 1.0
System velocity	γ	[km s^{-1}]	19.5 ± 2.0
Binary mass function	$f(M)$	[$M_\odot$]	0.27
Subdwarf mass	M_{sdB}	[$M_\odot$]	> 0.49
Orbital inclination	i	[°]	$67 - 90$
Companion mass	M_{comp}	[$M_\odot$]	> 0.74
Separation	a	[$R_\odot$]	0.6
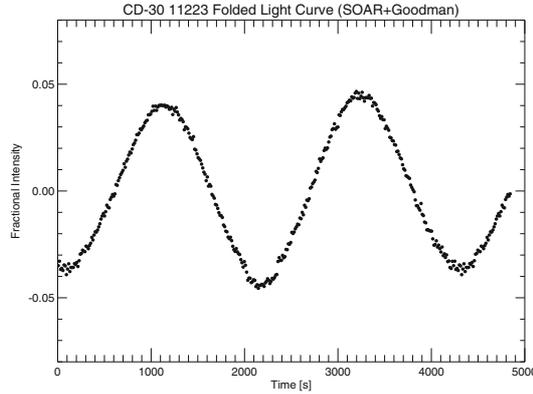
Figure 4. V-band light curve of CD−30°11223 taken with SOAR/Goodman and folded to the orbital period (from [20]).

observing conditions, which did not allow to observe the main targets, two medium resolution spectra ($R \simeq 2200, \lambda = 4450$–$5110$) were taken consecutively with the EFOSC2 spectrograph mounted on the ESO/NTT at June 10, 2012. The spectra showed a very high radial velocity shift ($\simeq 600\,\text{km s}^{-1}$), which called for immediate follow-up to obtain time-series spectroscopy and photometry. A long photometric time-series from the SuperWASP planetary transit survey public archive was readily available and extensive time-series spectroscopy (e.g. with the William Herschel telescope in La Palma) were obtained on short notice.

While the visible primary star is a typical sdB, the binary properties of this system are unique [20]. The orbital period of only 1.17 hours is by far the shortest of any sdB binary, and displays the largest radial velocity semi-amplitude of 376.6 km s^{-1} (see Fig. 3). The orbital and atmospheric parameters of the sdB were measured from time-series spectroscopy and allow to constrain the binary parameters (see Table 1). The SuperWASP light curve displayed variations due to the ellipsoidal deformation of the sdB star. This means that the companion must be a compact object, probably a white dwarf, the tidal drag of it causing the deformation of the sdB star. It was deemed that the system might be eclipsing. However, the SuperWASP data were of insufficient quality to conclude. Therefore a new light curve was obtained with the SOAR telescope and eclipses were indeed detected (see Fig. 4). An analysis of the optical light

curve is ongoing and will constrain the inclination of the system ($70 - 90°$). Combining all these results, the mass of the sdB ($> 0.49\ M_\odot$) and the mass of the WD companion ($> 0.74\ M_\odot$) will be constrained, as well as the separation of the components ($0.6\ R_\odot$); see Table 1 for other parameters of the system. Similar results were derived by [21].

The future evolution of this binary is particularly interesting since it can be a progenitor of a SN Ia via the so-called sub-Chandrasekhar double-detonation scenario [22]. In this scenario, the ignition of He-burning on the surface of an accreting WD is predicted to trigger carbon-burning in the core even if the star is less massive than the Chandrasekhar limit. The extremely short orbital period and small separation imply that the sdB star is close to fill its Roche-lobe. The surface gravity determined with the spectroscopic analysis of CD$-30°11223$ implies a radius of $0.17 R_\odot$, which corresponds to 85% of the Roche-lobe radius $R_{Roche} \sim 0.2 R_\odot$.

Due to gravitational wave radiation the orbit will shrink and Roche-lobe overflow will start in about 30 Myrs, much shorter than the EHB life time of the sdB. Once about 0.1 $M_\odot$ of helium have accumulated on the C/O white dwarf, a helium detonation will be triggered that subsequently lits the C/O core.

5. SUMMARY AND CONCLUSIONS

We presented a selected highlights of research into hot subdwarf stars. The first discovery of a highly magnetic sdO star, the census of pulsating sdB stars in the *Kepler* field and the enigmatic sdB binaries discovered from *Kepler* light curves, as well as by the MUCHFUSS project, demonstrates that the field is florishing and rapidly progressing.

References

[1] Heber, U., ARAA **47**, (2009) 211
[2] Geier, S., these proceedings, (2012)
[3] Kilkenny, D., Jeffery, C.S., & Koen, C., *Fifth Meeting on Hot Subdwarf Stars and Related Objects* (ASPC 452, San Francisco, 2012)
[4] Elkin, V.G., A&A **312**, (1996) L5
[5] Elkin, V.G., Contributions of the Astronomical Observatory Skalnate Pleso **27**, (1998) 452
[6] O'Toole, S.J., Jordan, S., Friedrich, S., & Heber, U., A&A **437**, (2005) 227
[7] Chountonov, G., & Geier, S., APSC **452**, (2012) 93
[8] Petit, P., Van Grootel, V., Bagnulo, S., et al., ASPC **452**, (2012) 87
[9] Mathys, G., Hubrig, S., Mason, E., et al., Astronomische Nachrichten **333**, (2012) 30
[10] Landstreet, J.D., Bagnulo, S., Fossati, L., Jordan, S., & O'Toole, S.J., A&A **541**, (2012) A100
[11] Gaensicke, B. et al. 2012, in prep.
[12] Østensen, R.H., Silvotti, R., Charpinet, S., et al., MNRAS **414**, (2011) 2860
[13] Bloemen, S., Marsh, T.R., Østensen, R.H., et al., MNRAS **410**, (2011) 1787
[14] Han, Z., Podsiadlowski, P., Maxted, P.F.L., & Marsh, T.R., MNRAS **341**,(2003) 669
[15] Geier, S., Hirsch, H., Tillich, A., et al., A&A **530**, (2011) A28
[16] Geier, S., Schaffenroth, V., Drechsel, H., et al., ApJL **731**, (2011) L22
[17] Geier, S., Schaffenroth, V., Hirsch, H., et al., ASPC **452**, (2012) 129
[18] Beuermann, K., Dreizler, S., Hessman, F.V., & Deller, J., A&A **543**, (2012) A138
[19] Vennes, S., Kawka, A., & Németh, P., MNRAS **410**, (2011) 2095
[20] Geier, S., Marsh, T.R., Dunlap, B.H., et al., arXiv:1209.4740 (2012)
[21] Vennes, S., Kawka, A., O'Toole, S.J., Nemeth, P., & Burton, D., arXiv:1210.1512 (2012)
[22] Fink, M., Röpke, F.K., Hillebrandt, W., et al., A&A **514**, (2010) A53