**Research Article**

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# News from the EREBOS project

**Abstract:** Planets and brown dwarfs in close orbits will interact with their host stars, as soon as the stars evolve to become red giants. However, the outcome of those interactions is still unclear. Recently, several brown dwarfs have been discovered orbiting hot subdwarf stars at very short orbital periods of 0.065 - 0.096 d. More than 8% of the close hot subdwarf binaries might have sub-stellar companions. This shows that such companions can significantly affect late stellar evolution and that sdB binaries are ideal objects to study this influence. Thirty-eight new eclipsing sdB binary systems with cool low-mass companions and periods from 0.05 to 0.5 d were discovered based on their light curves by the OGLE project. In the recently published catalog of eclipsing binaries in the Galactic bulge, we discovered 75 more systems. We want to use this unique and homogeneously selected sample to derive the mass distribution of the companions, constrain the fraction of sub-stellar companions and determine the minimum mass needed to strip off the red-giant envelope. We are especially interested in testing models that predict hot Jupiter planets as possible companions. Therefore, we started the EREBOS (Eclipsing Reflection Effect Binaries from the OGLE Survey) project, which aims at analyzing those new HW Vir systems based on a spectroscopic and photometric follow up. For this we were granted an ESO Large Program for ESO-VLT/FORS2. Here we give an update on the the current status of the project and present some preliminary results.

**Keywords:** hot subdwarf stars, low-mass stellar companions, sub-stellar companions

## 1 Introduction

Sub-luminous B stars (sdBs) are core helium-burning stars with very thin hydrogen envelopes and masses around $0.5$ $M_\odot$ (Heber 2009, 2016). To form such an object, the hydrogen envelope of the red-giant progenitor must be stripped

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off almost entirely. Since a high fraction of the sdB stars are members of short-period binaries (Maxted et al. 2001), common envelope ejection triggered by a close stellar companion is regarded as the most probable formation channel. However, growing evidence suggests that sub-stellar companions may have a significant influence on the still unclear formation of sdBs as well.

It has been proposed that planets and brown dwarfs could be responsible for the loss of envelope mass in the red-giant phase of the sdB progenitors (Soker 1998). As soon as the host star evolves to become a red giant, close sub-stellar companions must enter a common envelope. Whether those objects are able to eject the envelope and survive, evaporate or merge with the stellar core depends mostly on their masses. While planets below $1 - 10\,M_{\rm Jup}$ might not survive the interactions depending on the initial separation, planets and brown dwarfs exceeding this mass might be able to eject the envelope and survive as close companions. Nelemans and Tauris (1998) did a similar calculation for low-mass white dwarfs, coming to the conclusion that in this case companions with masses greater than $\sim 20\,M_{\rm Jup}$ can survive.

Sub-stellar companions around pulsating and close binary sdBs might have been found (e.g., Silvotti et al.

2007), but these would be too far away from their hosts for such interactions. Charpinet et al. (2011) and Silvotti et al. (2014) discovered possible earth-size objects in close orbits around pulsating sdBs, which might be the remnants of more massive planets destroyed during the common envelope phase.

The best evidence for interactions with sub-stellar companions is provided by the discovery of three close, eclipsing sdB binaries (HW Vir systems) with brown dwarf companions. The most successful way to detect such systems, which also show a characteristic sinusoidal light curve variation caused by the reflection effect, is by inspecting their light curves (e.g., Schaffenroth et al. 2013; Barlow et al. 2013).

Photometric and spectroscopic follow-up observations of the sdB binary J162256+473051 revealed that the system is eclipsing with a period of 0.069 d and the companion is likely a brown dwarf (Schaffenroth et al. 2014b). The short period system J082053+000843 (0.096 d) is also eclipsing and the companion has a mass between 45 and 67 $M_{Jup}$ (Geier et al. 2011). Another pulsating HW Vir system (V2008-1753, 0.065 d) with a brown dwarf companion has been discovered most recently (Schaffenroth et al. 2015). Moreover, two brown dwarf candidates around sdB stars have been detected (with periods $\sim$ 0.3 d, Schaffenroth et al. 2014a). Since those systems are not eclipsing only minimum masses can be derived for their companions (0.048 and 0.027 $M_\odot$), which are well below the hydrogen burning limit.

A photometric follow-up of spectroscopically selected targets (Schaffenroth et al., submitted) also allowed us to determine the fraction of sub-stellar companions around sdB stars. We derived a fraction of > 8% for sub-stellar companions in close sdB binaries. Moreover, they seem to be at least as frequent as low-mass stellar companions.

This shows that close sub-stellar companions are able to eject a red-giant envelope and that they are much more frequent than predicted by standard binary population synthesis theory. Due to this high fraction of close sub-stellar companions hot subdwarfs are very well suited for studying the interactions between stars and brown dwarfs or giant planets. To understand both the common envelope phase under extreme conditions and the role of close-in planets and brown dwarfs for late stellar evolution, we need to study a homogeneously selected large sample of eclipsing sdB binaries.

# 2 The current sample of close sdB binaries with cool companions

The known sample of eclipsing and non-eclipsing systems is quite inhomogeneous. Most of them have been found in photometric surveys due to their characteristic lightcurve variations (e.g., Schaffenroth et al. 2013) or in surveys used to find sdB pulsators (e.g., Jeffery and Ramsay 2014).
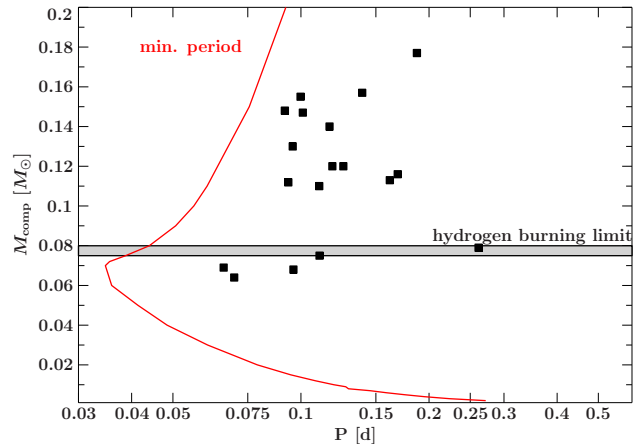


**Figure 1.** Period-companion mass diagram of the known HW Vir systems. The gray area marks the hydrogen-burning limit. Companions with smaller masses are sub-stellar. The red, solid line gives the minimum period at which a companion of a certain mass can exist. This was calculated assuming that the companions cannot exceed its Roche radius.

Figure 1 shows the companion masses of the analyses HW Vir systems plotted against their orbital periods. There is no obvious correlation between companion mass and period. However, the confirmed sub-stellar companions seem to be found preferentially in the shortest-period systems. If we assume that the radius of the companion cannot exceed its Roche radius, we can derive the minimum period possible for a system consisting of an sdB and a companion of a certain mass. To derive the Roche radius we used the formula by Eggleton (1983), which depends on the mass ratio and separation of the binary. For the radius of the companion we used the mass-radius relation by Baraffe et al. (1998). It can be seen that the minimum period for an sdB with a cool, low-mass companion is reached for companions in the brown dwarf mass range. Companions with masses of a few Jupiter masses on the other hand can only exist at longer periods of 0.2 to 0.25 d.

For non-eclipsing systems, the absolute mass of the companion cannot be determined. Assuming the canonical mass of 0.47 $M_\odot$, however, a minimum mass can be
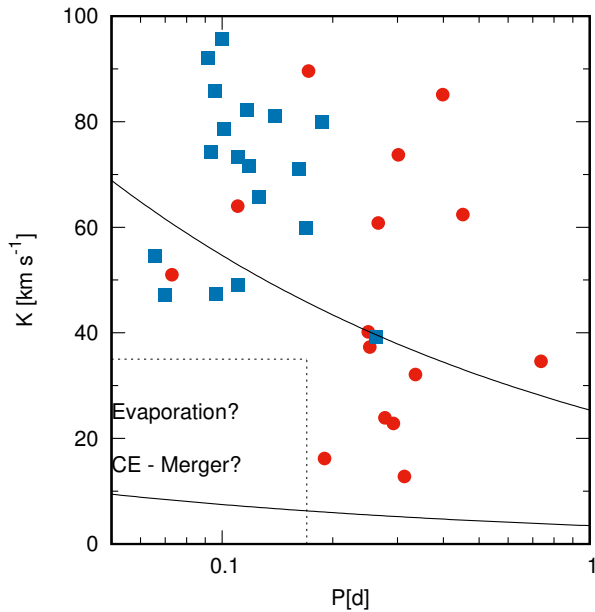
**Figure 2.** This figure is an updated version of Figure 4 from Schaffenroth et al. (2014a). It shows the RV semiamplitudes of all known sdB binaries with reflection effects and spectroscopic solutions plotted against their orbital periods. Blue squares mark eclipsing sdB binaries of HW Vir type where the companion mass is well constrained. Red circles mark systems without eclipses, where only lower limits can be derived for the companion masses. The lines mark the regions to the right where the minimum companion masses derived from the binary mass function (assuming 0.47 $M_\odot$ for the sdBs) exceed 0.01 $M_\odot$ (lower curve) and 0.08 $M_\odot$ (upper curve).

derived. An overview of the 31 sdB binaries with reflection effects and known orbital parameters is shown in Figure 2. Although only minimum masses can be derived for most of the companions, we can use this sample to do some statistics. While most companions are late M-dwarfs with masses close to $\sim 0.1\,M_\odot$, there is no sharp drop below the hydrogen-burning limit. The fraction of close sub-stellar companions is substantial. An obvious feature in Figure 2 is the lack of binaries with periods shorter than $\sim 0.2$ d and $K < 50\,\mathrm{km\,s^{-1}}$ corresponding to companion masses of less than $\sim 0.06\,M_{\mathrm{Jup}}$. Since the eclipses of a giant planet and a star close to the hydrogen-burning limit are of equal depth, this feature is not caused by selection effects. An explanation for the lack of objects at short periods could be that the companion triggered the ejection of the envelope, but was destroyed during the common-envelope phase. This could also explain the formation of some of the single sdB stars.

## 3 The EREBOS project

To study the properties of the population of hot subdwarf stars with low-mass stellar or sub-stellar companions, a large and homogeneously selected sample of eclipsing binaries is essential.

Thirty-six new HW Vir candidates have been discovered by the OGLE project (Pietrukowicz et al. 2013; Soszyński et al. 2015), tripling the number of such objects and providing the first such sample of eclipsing sdB stars. The stars have been identified by their blue colors and their characteristic light curve shapes in the I-band. These light curve shapes and the derived orbital periods leave no doubt that they are indeed HW Vir systems.

Most recently (Soszyński et al. 2016) published a catalog of 450 000 eclipsing systems in the Galactic bulge. We selected binaries with orbital periods $P < 1$ d and applied a color cut V-I < 1 mag. The resulting lightcurves ($\sim 10\,000$) were phased and inspected by eye. In this way we discovered 55 new HW Vir system candidates.

This sample together with the HW Vir candidates found by Pietrukowicz et al. (2013) and Soszyński et al. (2015) was then used to train a machine-learning algorithm. In this way another 20 systems were identified increasing the sample to 111 HW Vir candidates. This increases the sample of known HW Vir systems by a factor of more than five and is providing a large homogeneously selected sample for the first time. There might be a hidden population of hot white dwarf primaries with cool, low mass companions, especially at longer periods, which have similar lightcurves showing large reflection effects. Therefore our sample is still preliminary at this point.

To investigate this unique sample we started the EREBOS (Eclipsing Reflection Effect Binaries from the OGLE Survey) project that is aimed at measuring orbital and atmospheric parameters for as many of these systems as possible. The most crucial part of the project is time-resolved spectroscopy of these rather faint and short-period binaries.

We were awarded an ESO Large Program of 110h duration with FORS2@VLT to obtain accurate radial velocity curves for the 23 systems with the shortest periods. A combined analysis of the time-resolved spectroscopy together with the lightcurves will allow us to determine the masses of both components and the separations of the systems.

In addition, we started a photometric follow-up campaign using mostly 2-4m telescopes (ESO-NTT/Ultracam, SOAR/Goodman and SOAR SOI, SAAO-1.9m/SHOC). Moreover, radial velocity curves of five longer-period systems were already taken.

# 4 First results

In Figure 3 the magnitude distribution of the OGLE HW Vir candidates is shown in comparison to the known HW Vir systems. Most of the OGLE targets have magnitudes of $\sim 19$ mag, which is much fainter than the known HW Vir systems.
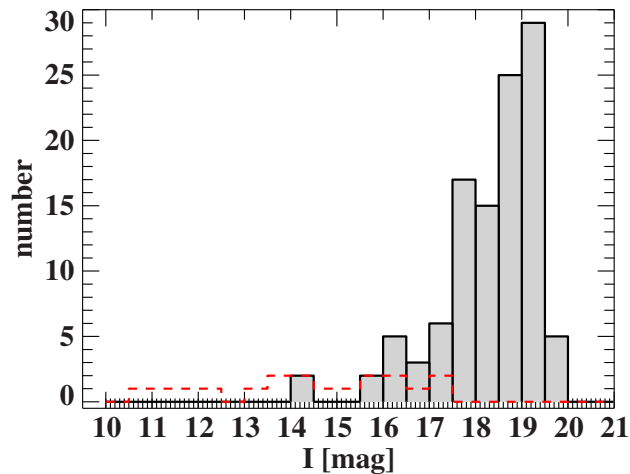
**Figure 3.** Magnitude distribution of the OGLE HW Vir candidates in comparison to the known HW Vir systems. The OGLE systems are shown in gray and the known systems by the red dashed line.

The OGLE sample is still contaminated by hot white dwarf binaries with cool, main sequence companions, which are showing similar lightcurves with large reflection effects. These are post-AGB equivalents to the post-RGB hot subdwarfs. Particularly, targets at longer periods with a reflection effect of large amplitude might not be explainable by hot subdwarf binaries, as they cannot heat up the companion to the temperatures necessary. Hence, the statistical interpretation of our sample is very preliminary and our results have to be treated cautiously, in particular at the longest periods. To solve this issue we are about to get spectroscopic confirmation of all OGLE targets.

Figure 4 shows the period distribution of the OGLE targets in comparison to the known HW Vir systems, which show a peak around 0.1 d. The period distribution of the OGLE targets looks quite different. The maximum is still found around 0.1 d. However, we also have a large population at longer periods from 0.25 to 0.5 d, which was not known before.

It is not surprising that the number of systems at larger periods is smaller as the eclipse probability decreases with increasing separation ($P$(eclipsing $= (R_1 + R_2)/a$). For the calculation of the eclipse probability we used the masses
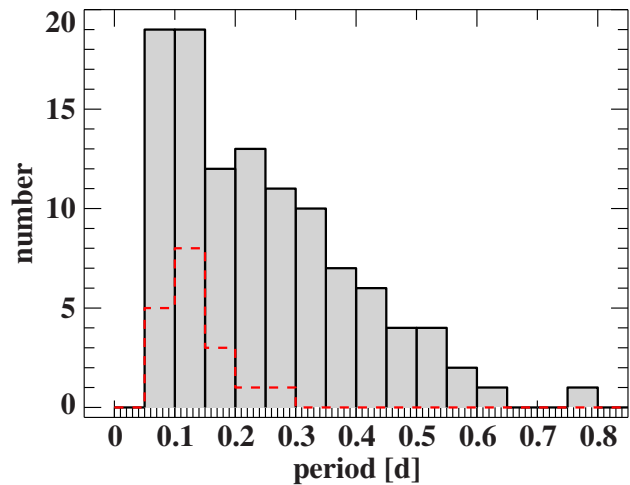
**Figure 4.** Period distribution of the OGLE HW Vir candidates in comparison to the known HW Vir systems. The OGLE systems are shown in grey and the known systems by the red dashed line.

and radii of the sdB and M dwarf companion of the prototype HW Vir. The eclipse probability was then used to correct the period distribution of the OGLE targets, to derive the unbiased period distribution of sdB systems with cool companions. This is shown in Figure 5. As not all systems have been confirmed yet, this figure is still preliminary. The period distribution shows a broad peak from 0.05 to 0.5 d with the maximum around 0.2 to 0.35 d. This means that the number of systems at longer periods is much larger than previously known.
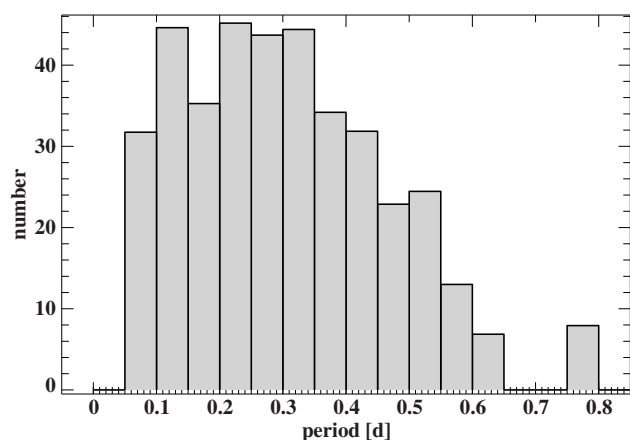
**Figure 5.** Preliminary period distribution of the OGLE HW Vir candidates corrected for the eclipse probability.

We used the spectral data of the observed OGLE targets to constrain the semi-amplitude of the radial velocity curve. This was combined with an analysis of the OGLE lightcurves to constrain the inclination angle. By assum-

ing a typical mass of an sdB of 0.47 $M_\odot$ we were able to derive a preliminary period-companion mass diagram of the OGLE targets. This diagram is shown in Figure 6. Similar to the period-companion mass diagram of the known HW Vir systems there is no correlation between companion mass and period. However, at shorter periods below 0.1 d the number of sub-stellar candidates is substantial and about equal to the number of M dwarf companions.
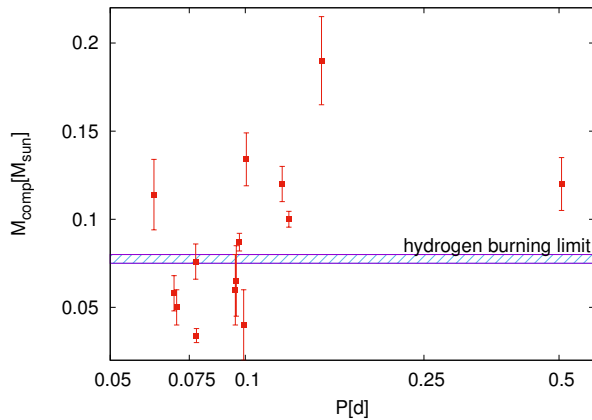


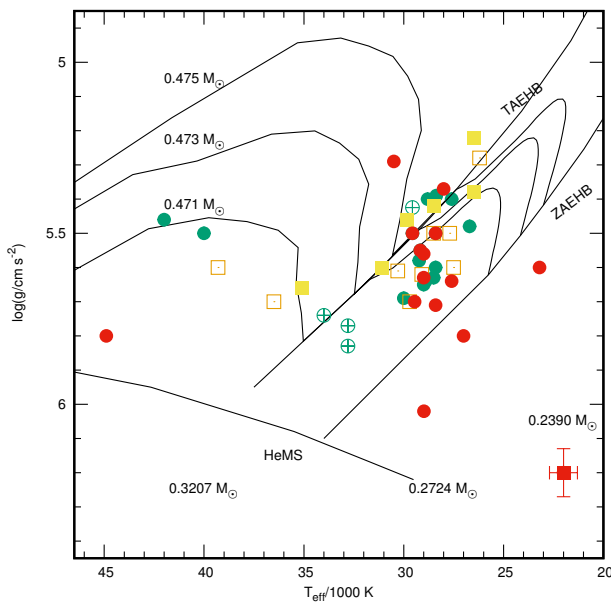**Figure 6.** Preliminary period-companion mass diagram of the OGLE HW Vir systems with radial velocity curves.



**Figure 7.** $T_{\text{eff}}$ − log $g$ diagram of primaries of the reflection effect systems with known parameters. Open symbols represent pulsating systems. The green circles represent the known HW Vir systems, and the yellow squares represent the systems without eclipses. The red circles represent the analyzed HW Vir systems from the OGLE survey. The red square gives the typical statistical uncertainties.

The spectra of the OGLE targets were also used to derive atmospheric parameters. These parameters were compared to the parameters of the known HW Vir systems (see Figure 7). The diagram shows that the distribution of the OGLE HW Virs looks different in the $T_{\text{eff}}$ − log $g$ diagram. The stars are distributed all over the extreme horizontal branch. This could mean that some of the OGLE HW Virs were formed by higher mass progenitors, while the known HW Virs, which are found in a very distinct area of the $T_{\text{eff}}$ − log $g$ diagram, might have had similar progenitors. However, no targets at the hotter end of the EHB have been found yet.

# 5 Conclusions

We started the EREBOS project to study a large sample of homogeneously selected HW Vir systems from the OGLE survey. We plan a photometric and spectroscopic follow-up of as many targets as possible to determine the fundamental ($M$, $R$), atmospheric ($T_{\text{eff}}$, log $g$) and binary parameters ($a$, $P$). At the moment we already have RV data for 23 objects.

The data analysis turned out to be less straightforward than expected as we have some problems with the enormous crowding in the Galactic bulge field, which complicates photometry as well as spectroscopy. Moreover, the ESO-VLT/FORS2 spectrograph was not found to be as stable as expected, as it was not designed for the determination of radial velocities. This complicates the determination of radial velocity curves.

The main goal is to investigate the systems at the short-period end and the longer-period range of the period distribution to answer our key questions: Is there a well-defined minimum mass or a continuum ranging from the most massive brown dwarfs down to hot Jupiter planets? What is the fraction of close sub-stellar companions to sdB stars and how does it compare with the possible progenitor systems like main sequence stars with brown dwarf or Jupiter-like companions? Moreover, we also need to get a better understanding of the common envelope phase. Another future goal is a physical model of the reflection effect, which we hope to achieve with this huge sample of reflection effect binaries. For this goal it is necessary to numerically model the radiation emitted from the heated hemisphere of the companion star rather than use a simple albedo approach as has been done in Vučković et al. (2016) for a large sample of systems.

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