EXOTIME: searching for planets and measuring Pdot in sdB pulsators

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We review the status of the EXOTIME project (EXOplanet search with the Timing MEthod). The two main goals of EXOTIME are to search for sub-stellar companions to sdB stars in wide orbits, and to measure the secular variation of the pulsation periods, which are related to the evolutionary change of the stellar structure. Now, after four years of dense monitoring, we start to see some results and present the brown dwarf and exoplanet candidates V1636 Ori b and DW Lyn b.

1 Introduction

Subdwarf B (sdB) stars are extreme horizontal branch (EHB) core He-burning stars, and are characterized by an extremely thin H envelope (see Heber\(^4\) for a comprehensive review). They are the product of a small fraction of red giants (RGs), of the order of 1%, that loose almost all their envelope near the tip of the RG branch. While half of sdB stars are in binary systems and their formation can be explained in terms of binary evolution (Han et al.\(^3\) 2003, 2002; Soker\(^5\) 1998), it is more difficult to explain the formation of the other half of apparently single sdBs.

A planet with a sufficient mass (>10 M\(_{\text{Jup}}\)) and sufficiently close to the star may have enough energy and angular momentum to remove the RG envelope and trigger the formation of an sdB star. The opposite effects of stellar mass loss (which causes an outward drift of the planet) and tidal forces (which causes an inward drift), may create a gap in a certain range of orbital distances (e.g. Nordhaus et al.\(^6\) 2010). Presently, we know a handful of sdB stars (mainly single) that show some evidence of sub-stellar companions. They belong to three different groups, well distinct in terms of orbital distance and planetary mass. In order of increasing orbital distance we find: 1) at least five close brown dwarf (BD) candidates with orbital periods of the order of 1 day or less (Geier et al.\(^7\) 2012). 2) Two Earth-mass planet candidates around the sdB pulsator KIC 05807616, with orbital periods of 5.8 and 8.2 hours (Charpinet et al.\(^8\) 2011). 3) Six planet/BD candidates with minimum masses between ~2 and ~40 M\(_{\text{Jup}}\) in large orbits with orbital periods between 3.2 and ~16 yrs (Silvotti et al.\(^9\) 2007, Lee et al.\(^10\) 2009; orbital solutions significantly revised by Beuermann et al.\(^11\) 2012b; Qian et al.\(^12\) 2009; orbital solution improved by Beuermann et al.\(^13\) 2012a; Qian et al.\(^14\) 2012; Beuermann et al.\(^15\) 2012a).

These three groups correspond to three different detection methods: radial velocities (RVs), illumination effects, and timing (using either the stellar pulsation or the eclipses as a clock). Figure\(^16\) compares the sensitivities of these different detection methods.

The EXOTIME project is primarily oriented to increase the statistics of sdB planets/BDs in large orbits (third group) and particularly focuses on single stars which are not part of a binary system. The method is based on getting a dense coverage of time-series photometric data and searching for periodic (pulsation) phase variations due to the star wobble caused by a planet. It is the same method that has been used for V391 Peg (Silvotti et al.\(^17\) 2007). Obviously, the large data sets that we are collecting for our five EXOTIME targets allow to study also other pulsational properties of the star, in particular the stability of the pulsation periods (measuring their secular variation \(\dot{P}\)) and the amplitude variations, and to improve the star characterization through asteroseismology.

More details on the EXOTIME project can be found in Schuh et al.\(^18\) 2010 and on the EXOTIME web site at http://www.na.astro.it/~silvotti/exotime/. In this paper, we summarize the results obtained for the two new well-observed targets V1636 Ori and DW Lyn.

2 Methods

2.1 Observations

In order to measure secular period variations and to search for companions in wide orbits around sdB stars, we need to gather data spread over a very long time-baseline. Within EXOTIME, this is realized via a regular long-term monitoring of our targets with many small- to medium-class optical telescopes by means of time-resolved ground-based photometry. On average, data for each target are taken once a

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2 Methods

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Fig. 1 Substellar companions around subdwarf B stars (black dots) and comparison of the detection methods mentioned in the text (RV, illumination and timing). For most of these systems the inclination is not known and we report the minimum mass. Horizontal lines show 1 Jupiter mass, 13 Jupiter masses (dividing the exoplanet and brown dwarf regimes) and 75 Jupiter masses (dividing the substellar and stellar regimes). The big dots are the two candidates presented in this paper.

month on several consecutive nights, to achieve a sufficient frequency resolution within these observing blocks. Each of these blocks of roughly 3-5 nights finally yields one data point for the subsequent O–C analysis, which will be addressed in the next subsection.

The photometric data for V1636 Ori were taken with four different observatories yielding a total amount of 92.7 hours in the period from August 2008 to November 2010. DW Lyn was observed with ten different telescopes during November 2007 and November 2010 and the data sum up to 857.5 hours of photometry.

2.2 Data analysis

An O–C diagram is a way to investigate the temporal behavior of periodic events. In our case, these periodic events are the intensity variations due to the pulsations of the sdB stars. In contrast to the solar-like oscillations with random phases and short lifetimes, the pulsations of hot subdwarf stars are very stable on long timescales. This is a major prerequisite to conduct the phase analysis.

In general there may appear different components in an O–C diagram. Depending on their physical nature, these can be i) linear if the period is constant (with or without a slope depending if the guess period is wrong or right), ii) parabolic if the period is changing linearly with time, or iii) sinusoidal if the period increases and decreases periodically. The secular period change due to the momentary evolution of the star results in a parabolic O–C component. The same holds for the signature due to proper motion. The signature that a possible companion would induce is a sinusoidal O–C component due to the companion-induced wobble of the star around the common barycenter. Another effect resulting in a sinusoidal O–C component is the beating of close unresolved frequencies. All these possible components are thoroughly investigated in Lutz (2011). In order to finally obtain the O–C diagrams shown in Figs. 2 and 3 we i) subtracted the parabolic evolutionary component, ii) neglected the contribution due to proper motion since it is estimated to be two to three orders of magnitude weaker than the evolutionary component, iii) subtracted beating signals after confirming their presence with an independent method and iv) finally investigated these residual O–C diagrams for periodic signatures.

We refer to chapter 5 and chapter 6.3 in Lutz (2011) for a detailed description of the construction and analysis of the O–C diagrams shown here and especially for the treatment of the various different O–C components that have been mentioned above.

3 Status on individual targets

We present first results for the two targets V1636 Ori and DW Lyn. A previous status report is given in Lutz et al. (2011). Concerning the other EXOTIME targets, new data on V391 Peg and QQ Vir are under analysis.

3.1 V541 Hya (EC09582−1137)

This is a southern object and the least well observed target in the EXOTIME project (only approx. 15 hours of observations). The low declination of this star and the low amplitudes result in limited observabilities and a restriction to larger mirror-sizes (above 2 m). With the current low coverage, it would probably take a few more years to achieve reliable O–C diagrams.

3.2 QQ Vir (PG1325+101)

A status report on QQ Vir is given in Benatti et al. (2010). Encouraged by the short-term phase stability of this target, QQ Vir is now the highest priority target of EXOTIME. The data amount for this target, gathered between 2008 and 2011, sum up to roughly 124 hours of photometry and are currently under analysis.

3.3 V391 Peg (HS2201+2610)

Since the publication of a planetary companion candidate with a minimum mass of 3.2 Jupiter masses at an orbital distance of about 1.7 AU from its host star (Silvotti et al. 2007), we have continued to monitor this system in order to verify and consolidate our results. The new data are under analysis and an identification of the two main p-modes, based on ULTRACAM multicolor photometry, was presented by Silvotti et al. (2010).
Fig. 2 Phase-folded O–C diagrams for V1636 Ori based on the independent frequencies $f_1$ (top) and $f_2$ (bottom). Evolutionary and beating signals are already subtracted. The data are folded with an orbital period as given in the plots. Data points are duplicated on the phase-axis for plotting purposes.

3.4 V1636 Ori (HS0444+0458)

3.4.1 New results on evolutionary time scale

From the parabolic O–C component, we derive a $\dot{P}_1$ of $(9.300 \pm 0.0023) \cdot 10^{-12}$ d/d for $f_1$ (631.73495 1/d) and $\dot{P}_2$ of $(3.010 \pm 0.0010) \cdot 10^{-12}$ d/d for $f_2$ (509.97773 1/d). The proper motion contribution to the parabolic component is estimated to be at least two orders of magnitude smaller than the effect of period evolution (Lutz 2011). Hence, the proper motion is neglected in our analysis. These $\dot{P}$ values translate to evolutionary timescales of $T_{\text{evol},f_1} = 0.466 \pm 0.002$ Myr and $T_{\text{evol},f_2} = 1.785 \pm 0.006$ Myr for $f_1$ and $f_2$, respectively. From the positive sign of $\dot{P}$, we can tell that V1636 Ori is in an expansion phase. Additionally, the radial expansion timescale $R (\dot{P}/P \approx 3/2 \dot{R}/R)$ suggests that this star has probably already undergone core helium exhaustion (compare e.g. to Fig. 3 in Kawaler 2010).

3.4.2 New results on companion search

After subtracting the evolutionary component, we find sinusoidal signatures in the O–C diagram of both frequencies $f_1$ and $f_2$. The most plausible explanation for this sinusoidal behavior is an orbital origin, hence the presence of a companion candidate around V1636 Ori. Figure 3 shows the O–C diagrams for $f_1$ and $f_2$, phase-folded with an orbital period close to 72 days. Within the error bars, the same signature consistent in amplitude, phase and period is independently also seen in the O–C diagram for $f_2$. From the O–C amplitude and period we can derive the minimum companion mass and orbital separation. Assuming a canonical sdB mass of $0.47 M_\odot$ and weighting over the independent frequencies $f_1$ and $f_2$, we find a minimum mass $m \cdot \sin i$ of $31.41 \pm 7.25$ Jupiter masses for this candidate, V1636 Ori b, which would place it to the brown dwarf regime (see Fig. 4 for the effect of the unknown inclination on the true mass). The orbital separation is derived to be $0.269 \pm 0.001$ AU.

3.5 DW Lyn (HS0702+6043)

3.5.1 New results on evolutionary time scale

For DW Lyn we derive a $\dot{P}_1$ of $(2.871 \pm 0.0025) \cdot 10^{-13}$ d/d for $f_1$ (237.94106 1/d) and $\dot{P}_2$ of $(5.578 \pm 0.006) \cdot 10^{-12}$ d/d for $f_2$ (225.15882 1/d). The proper motion contribution
to the parabolic component is neglected here with the same argument as for V1636 Ori. The $P$ values translate to evolutionary timescales of $T_{\text{evol,}f_1} = 40.110 \pm 0.350$ Myr and $T_{\text{evol,}f_2} = 2.181 \pm 0.003$ Myr for $f_1$ and $f_2$, respectively. From the positive sign of $P$, we can tell that DW Lyn is in an expansion phase. Likewise for V1636 Ori, the radial expansion timescale $R$ for DW Lyn suggests that this star has probably also undergone core helium exhaustion.

### 3.5.2 New results on companion search

After subtraction of the evolutionary component we find sinusoidal signatures in the O–C diagram of both frequencies $f_1$ and $f_2$. The most plausible explanation for this sinusoidal behavior is again an orbital origin and a companion candidate around DW Lyn. Figure 3 shows the O–C diagrams for $f_1$ and $f_2$. Within the error bars, the same signature consistent in amplitude, phase and period is also seen in the O–C diagram for the independent frequency $f_2$. Weighting over the amplitudes and periods in the O–C diagrams of $f_1$ and $f_2$ results in a minimum companion mass of $5.58 \pm 1.44$ Jupiter masses for this candidate and an orbital separation of $1.148 \pm 0.050$ AU. Hence, DW Lyn b would most likely be in the exoplanet mass regime (see Fig. 4 for the effect of the unknown inclination on the true mass).

### 4 Summary

We present first results for the two EXOTIME targets V1636 Ori and DW Lyn, assuming that the parabolic component in the O–C diagram is due to evolution and that the sinusoidal residuals are the signature of sub-stellar companion candidates. The secular period change in the frequencies $f_1$ and $f_2$ in V1636 Ori reveals an expansion of the envelope with a timescale consistent with core helium exhaustion. The same conclusions are drawn for DW Lyn, also based on the two strongest frequencies $f_1$ and $f_2$ in this star. Concerning the search for sub-stellar companions, in both targets we find evidence for the presence of a companion in a rather wide orbit. The brown dwarf candidate V1636 Ori b has a minimum mass of 31.41 Jupiter masses and orbits the host star at a separation of 0.269 AU. The candidate DW Lyn b is most likely an exoplanet with a minimum mass of 5.58 Jupiter masses and with an orbital separation of 1.148 AU.

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