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The search for transiting planets around hot subdwarfs

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Abstract

The main goal of this project is to investigate star-planet interactions during the Red Giant Branch (RGB) phase. In particular, we focus on what happens to planetary systems once their host stars leave the main sequence and engulf close-in planets, presumably, perturbing the dynamical architecture of the system. In this context, we wonder if close-in planets may survive this evolutionary phase, evolving towards a new stable configuration, or on the contrary, if these planets are destroyed and the entire system collapses. Whatever the outcome, how will this interaction alter the star and affect its subsequent evolution? Here, we search for observational evidence of transiting planets orbiting hot subdwarfs (sdBs) stars, which are direct post-RGB objects that have lost most of their envelopes. To this end, we analyze light curves from the space missions Kepler/K2, TESS, and CHEOPS to search for shallow periodic transits of close-in, previously engulfed planets or their remnants, such as the rocky cores of giant gas planets. By determining the occurrence of planets or remnants around sdB stars, we will place strong constraints on the evolution of planetary systems after the RGB phase of their host stars.

This summary describes the methods, tools, and strategies used to explore the available photometric data in the search for transiting planets and establish detection limits that allow us to build planet occurrence rates around these stars.

Keywords: Hot subdwarfs stars, transiting exoplanets, Kepler/K2, TESS, CHEOPS

1. Introduction

The question of the evolution of planetary systems after the main sequence of their host is generally addressed by searching for exoplanets around evolved stars, i.e., sub-giants, RGB, and standard Horizontal Branch (HB–Red Clump) stars. However, these evolved stars are giant, with radii ranging from 5–10 to 1000 $R_\odot$ and have masses about 1.5 $M_\odot$. Hence, transit and radial velocity methods are very challenging to use, and in the best case, only able to detect giant and massive planets (Jones et al., 2021). Indeed, several studies found a dearth of close-in giant planets and a total lack of small close-in planets around evolved stars compared to solar-type main sequence stars (see, e.g., Sato et al., 2008). An alternative approach to studying the fate of planetary systems can also be addressed by studying white-dwarf stars, which is the ultimate fate of 97% of all stars. Orbiting these stars have been found disintegrating planetesimals and a transiting giant planet (Vanderburg et al., 2020). Statistics on the occurrence rate of planets around white dwarfs as a function of orbital period and planet radius have been established (Wilson et al., 2019). However, white dwarfs experience two giant phases of evolution: the RGB and the Asymptotic Giant Branch (AGB). AGB expansion and intense mass loss, followed by the planetary nebula phase, profoundly affect the orbital stability of any surrounding bodies. Consequently, such detected planets might correspond to first-generation, second-generation, or hybrid planets. That is, no direct conclusions on the fate of planetary systems when their host stars leave in the main sequence can be drawn by studying white dwarfs. On the contrary, sdB stars, thanks to their small sizes and masses combined with the fact they do not suffer AGB expansion, constitute excellent opportunities to address the question of the evolution of exoplanet systems after the RGB phase, that is, allowing us to obtain direct conclusions on the evolution of planetary systems just afterward the host star leaves the main sequence.

To date, no transit of an exoplanet or remnant has been detected around an sdB. Nevertheless, some detections have been claimed (see, e.g., Silvotti et al., 2007; Charpinet et al., 2011). However, they are highly debated by recent studies (Silvotti et al., 2018; Blokesz et al., 2019). The lack of clear evidence of exoplanets or remnants orbiting hot subdwarfs is mainly because no systematic surveys have been performed in the search for these objects. In this context, in Van Grootel et al. (2021) we carried out an in-depth feasibility study considering data from Kepler/K2, TESS and CHEOPS, and built our target list, which is displayed in Figure 1. We concluded that transiting objects with radius $\lesssim$1.0 $R_\oplus$ can be detected in most Kepler/K2 and CHEOPS targets for orbital periods shorter than one day. We found that sub-Earth size objects down to 0.3 $R_\oplus$ might be detectable in the best scenarios. For TESS targets, while being the mission providing the largest sample of observed targets, its poorer photometric quality yields detections of $\lesssim$1.5 $R_\oplus$ when using one or two sectors, but sub-Earth sizes may be reached when combining more sectors.

2. Strategies, methods and tools

2.1. The Kepler/K2 & TESS surveys and the CHEOPS filler program

We are systematically analyzing the sdB stars to date observed by Kepler/K2 & TESS surveys to search for shallow periodic transits of planetary origin by means of our `SHERLOCK` pipeline (described in the following section). In short, about 2500 sdBs have been observed by these missions. About 70 were observed in the original Kepler field, and 170 were in the K2 mission. TESS, accounting for the 2-years primary mission and extended mission (started in June 2020), has observed about 2200 sdBs, a number that increases with each new sector ob-

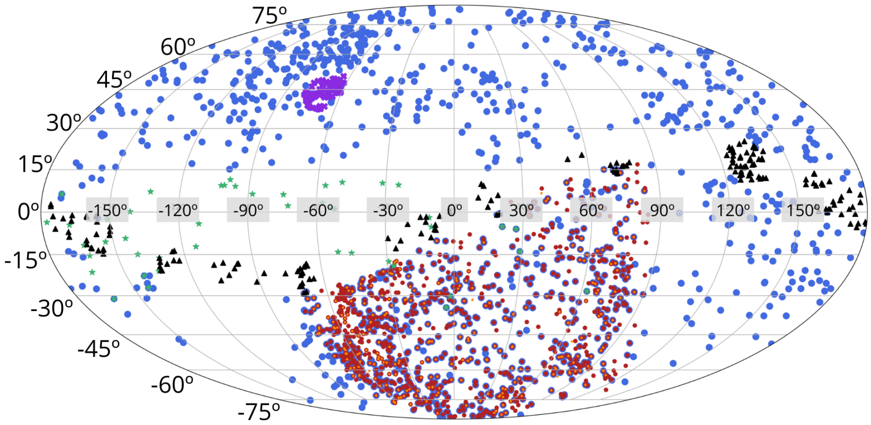

Figure 1: Celestial distribution of our hot subdwarfs sample: TESS primary mission (blue dots), TESS extended mission 2-min and 20 s (red and dark orange dots), Kepler (purple crosses), K2 (black triangles), and CHEOPS (green stars) from Van Grootel et al. (2021).

served during the current extended mission. Recently we published our analyses corresponding to the exploration of the 792 sdBs observed during the TESS cycle 1 (Thuillier et al., 2022), where we found some tentative planetary signals, which we are following up using ground-based telescopes to confirm or refute them. For the first time, this study allowed us to set upper limits to the planet occurrence rates orbiting these stars as a function of the planetary radius and orbital period.

In addition, we have a filler program in CHEOPS, which is observing a selected sample of 60 bright sdBs. The high-precision photometry provided by CHEOPS allows us to search for extremely small planets or remnants whose sizes might be down to Mars's size. In this context, our filler program aims to reach for each star in our sample a phase coverage ∼80% for a hypothetical planet with five days orbital period (see Figure 2).

2.2. Searching for planets using the `SHERLOCK` pipeline

`SHERLOCK` (**S**earching for **H**ints of **E**xoplanets f**R**om **L**ightcurves **O**f spa**C**e-based see**K**ers) code is an end-to-end pipeline that allows the users to explore the data from space-based missions (Kepler/K2 and TESS) to search for planetary candidates (Pozuelos et al., 2020). It can be used to recover alerted candidates by the automatic pipelines such as the Science Processing Operations Center (SPOC) and the Quick Look Pipeline (QLP), the so-called Kepler objects of interest (KOIs), and TESS objects of interest (TOIs), and to search for candidates that remain unnoticed due to detection thresholds, lack of data exploration or poor photometric quality. To this end, `SHERLOCK` has six different modules to (1) acquire and prepare the light curves from their online repositories, (2) search for planetary candidates, (3) vet the interesting signals, (4) perform a statistical validation, (5) model the signals to refine their ephemeris, and (6) compute the observational windows from ground-based observatories to trigger a follow-up campaign. To execute all these modules, the user only needs to fill in an initial `yaml` file with some basic information such as the star ID, the cadence to be used, etc., and use sequentially a few lines of code to pass from one step to the next.

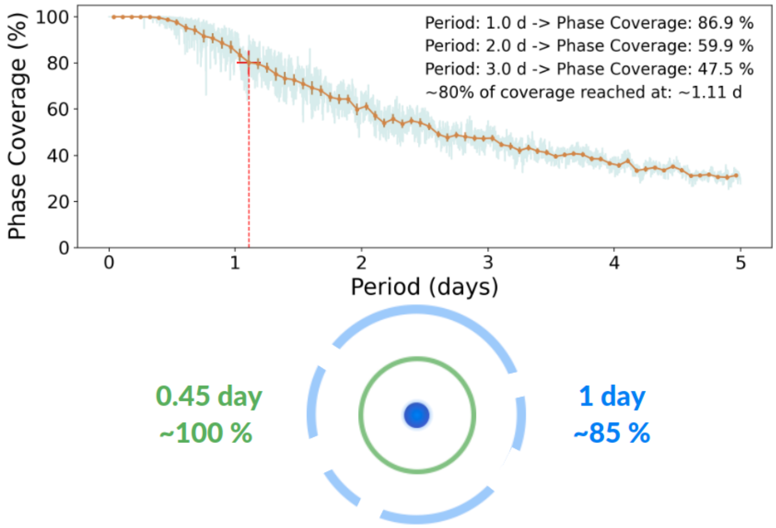

Figure 2: *Top:* CHEOPS' phase coverage (in %) as a function of orbital period reached for our candidate HD 149382 after 18x2 orbits. The blue line represents the full range of 5000 periods explored, and the orange line is the binning of each ∼1.7 hr. The orbital period for which the phase coverage is ∼80% is marked with the dotted vertical red line. *Bottom:* graphical visualization of the phase coverage for a hypothetical planet with orbital periods of 0.45 days (green circle) and 1 day (blue circle) with phase coverages of ∼100% and ∼85%, respectively.

To optimize the transit search and remove any undesired trend, `SHERLOCK` uses a multi-detrend approach, implemented via the `wotan` package (Hippke et al., 2019), whereby the nominal PDCSAP light curve, which is obtained from the Mikulski Archive for Space Telescopes (MAST), is detrended several times using a biweight filter by varying the window size. Each new detrended light curve, jointly with the nominal PDCSAP flux, is processed by the Transit Least Squares package (`tls`; Hippke and Heller, 2019), which is optimized for detecting shallow periodic transits using an analytical transit model based on stellar parameters. Then, `tls` is more efficient for bluer stars where transit shapes diverge from the typical box shape. The multi-detrend approach is motivated by the risk of removing transit signals when we detrend the light curves, particularly short and shallow ones. Hence, with this strategy, we converged on the most efficient detrend, which allowed us to find signals with the best signal-to-noise ratio (S/N) and signal-detection-efficiency (SDE).

2.3. Establishing detection limits with `MATRIX`

To study the detection limits of a given data set, we perform injection-and-recovery experiments using our `MATRIX` (**M**ulti-ph**A**se **T**ransits **R**ecovery from **I**njected e**X**oplanets) code (Dévora-Pajares and Pozuelos, 2022). `MATRIX` injects synthetic planets into a given light curve. The injected planets are generated in a Radius–Period–Phase parameter space, whose limits and steps are defined by the user according to the particular goal of each study. For example, in our feasibility study presented in (Van Grootel et al., 2021), for the TESS data, we focus on radii ranging from 0.5 to 3.0 $R_{\oplus}$ with steps of 0.05 $R_{\oplus}$, and periods from 1.0 to 6.0 d with steps of

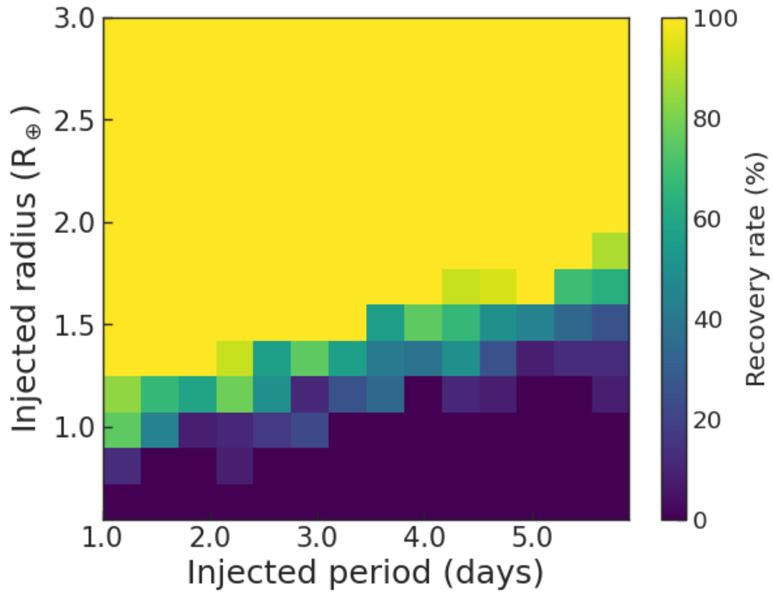

Figure 3: Injection-and-recovery experiment performed using `MATRIX` to test the detectability of transiting planets orbiting TIC 96949372 using two TESS sectors (Van Grootel et al., 2021). Larger recovery rates are presented in yellow and green colors, while lower recovery rates are shown in blue and darker hues. Planets smaller than 1.0 $R_\oplus$ would remain undetected for the explored periods, while transiting planets larger than 2.0 $R_\oplus$ have recovery rates of 100%, since we did not find any, we can rule out the presence of such transiting planets.

0.1 d. Then, the light curves containing synthetic planets are processed in the search for planets using the `tls` algorithm. For each detection, `MATRIX` stores the period and epoch, and they are compared with the injected ones. A synthetic planet is recovered when its epoch matches the injected epoch with 1 hour accuracy, and its period is within 5% of the injected period. In addition, for each period found that did not match the injected period, `MATRIX` checked if it could correspond to the first harmonic ($2\times P_{\mathrm{injected}}$) or sub-harmonic ($P_{\mathrm{injected}}/2$). If this is the case, the signal is also considered recovered. For simplicity, the synthetic planets are injected assuming their impact parameters and eccentricities equal zero. Moreover, `MATRIX` allows the user to detrend the light curves using a bi-weight filter to remove any flux variability that might hinder the planetary search. An example of these experiments is shown in Figure 3 for the particular case of TIC 96949372, using two TESS sectors.

3. Conclusions

In this summary, we presented the current status of our project, in which the main goal is to find the first evidence of a transiting planet orbiting an sdB star. Moreover, we introduced our dedicated CHEOPS survey and our tools `SHERLOCK` and `MATRIX`, which are used to easily search for planets in Kepler/K2 & TESS data, and establish robust detection limits, respectively. Our recent results allowed us to set for the first time upper limits to the planet occurrence rates orbiting these stars as a function of planetary radius and orbital period based on TESS cycle

1. This result will be updated and better constrained by adding the results coming from our exploration of TESS cycle 2 and Kepler/K2 data, which is currently ongoing. These results will provide unique insights into the fate of known planetary systems with close-in exoplanets that orbit main-sequence stars, allowing us to build a robust planetary formation and evolution model, taking into account the stellar evolution beyond the main sequence.

Further Information

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Author contributions

VG is the PI of the project and of the CHEOPS' filler program. FJ is the project's co-coordinator, analyses CHEOPS data, and participates in the constant development of `SHERLOCK` and `MATRIX` codes. AT is in charge of running `SHERLOCK` in the search for planets over the TESS data. MDP is the main developer of `SHERLOCK` and `MATRIX` and participates in searching for planetary candidates in TESS data.

Conflicts of interest

The authors declare no conflict of interest.

References

Blokesz, A., Krzesinski, J. and Kedziora-Chudczer, L. (2019) Analysis of putative exoplanetary signatures found in light curves of two sdBV stars observed by *Kepler*. Astronomy & Astrophysics, 627, A86. https://doi.org/10.1051/0004-6361/201835003.

Charpinet, S., Fontaine, G., Brassard, P., Green, E. M., Van Grootel, V., Randall, S. K., Silvotti, R., Baran, A. S., Østensen, R. H., Kawaler, S. D. and Telting, J. H. (2011) A compact system of small planets around a former red-giant star. Nature, 480(7378), 496–499. https://doi.org/10.1038/nature10631.

Dévora-Pajares, M. and Pozuelos, F. J. (2022) MATRIX: Multi-phAse Transits Recovery from Injected eXoplanets. Zenodo [software]. https://doi.org/10.5281/zenodo.6570831.

Hippke, M., David, T. J., Mulders, G. D. and Heller, R. (2019) Wōtan: Comprehensive time-series detrending in Python. The Astronomical Journal, 158(4), 143. https://doi.org/10.3847/1538-3881/ab3984.

Hippke, M. and Heller, R. (2019) Optimized transit detection algorithm to search for periodic transits of small planets. Astronomy & Astrophysics, 623, A39. https://doi.org/10.1051/0004-6361/201834672.

Jones, M. I., Wittenmyer, R., Aguilera-Gómez, C., Soto, M. G., Torres, P., Trifonov, T., Jenkins, J. S., Zapata, A., Sarkis, P., Zakhozhay, O., Brahm, R., Ramírez, R., Santana, F., Vines, J. I., Díaz, M. R., Vučković, M. and Pantoja, B. (2021) Four Jovian planets around low-luminosity giant stars observed by the EXPRESS and PPPS. Astronomy & Astrophysics, 646, A131. https://doi.org/10.1051/0004-6361/202038555.

Pozuelos, F. J., Suárez, J. C., de Elía, G. C., Berdiñas, Z. M., Bonfanti, A., Dugaro, A., Gillon, M., Jehin, E., Günther, M. N., Van Grootel, V., Garcia, L. J., Thuillier, A., Delrez, L. and Rodón, J. R. (2020) GJ 273: on the formation, dynamical evolution, and habitability of a planetary system hosted by an M dwarf at 3.75 parsec. Astronomy & Astrophysics, 641, A23. https://doi.org/10.1051/0004-6361/202038047.

Sato, B., Toyota, E., Omiya, M., Izumiura, H., Kambe, E., Masuda, S., Takeda, Y., Itoh, Y., Ando, H., Yoshida, M., Kokubo, E. and Ida, S. (2008) Planetary companions to evolved intermediate-mass stars: 14 Andromedae, 81 Ceti, 6 Lyncis, and HD167042. Publications of the Astronomical Society of Japan, 60, 1317–1326. https://doi.org/10.1093/pasj/60.6.1317.

Silvotti, R., Schuh, S., Janulis, R., Solheim, J. E., Bernabei, S., Østensen, R., Oswalt, T. D., Bruni, I., Gualandi, R., Bonanno, A., Vauclair, G., Reed, M., Chen, C. W., Leibowitz, E., Paparo, M., Baran, A., Charpinet, S., Dolez, N., Kawaler, S., Kurtz, D., Moskalik, P., Riddle, R. and Zola, S. (2007) A giant planet orbiting the 'extreme horizontal branch' star V 391 Pegasi. Nature, 449(7159), 189–191. https://doi.org/10.1038/nature06143.

Silvotti, R., Schuh, S., Kim, S. L., Lutz, R., Reed, M., Benatti, S., Janulis, R., Lanteri, L., Østensen, R., Marsh, T. R., Dhillon, V. S., Paparo, M. and Molnar, L. (2018) The sdB pulsating star V391 Peg and its putative giant planet revisited after 13 years of time-series photometric data. Astronomy & Astrophysics, 611, A85. https://doi.org/10.1051/0004-6361/201731473.

Thuillier, A., Van Grootel, V., Dévora-Pajares, M., Pozuelos, F. J., Charpinet, S. and Siess, L. (2022) A search for transiting planets around hot subdwarfs. II. Supplementary methods and results from TESS Cycle 1. Astronomy & Astrophysics, 664, A113. https://doi.org/10.1051/0004-6361/202243554.

Van Grootel, V., Pozuelos, F. J., Thuillier, A., Charpinet, S., Delrez, L., Beck, M., Fortier, A., Hoyer, S., Sousa, S. G., Barlow, B. N., Billot, N., Dévora-Pajares, M., Østensen, R. H., Alibert, Y., Alonso, R., Anglada Escudé, G., Asquier, J., Barrado, D., Barros, S. C. C., Baumjohann, W., Beck, T., Bekkelien, A., Benz, W., Bonfils, X., Brandeker, A., Broeg, C., Bruno, G., Bárczy, T., Cabrera, J., Cameron, A. C., Charnoz, S., Davies, M. B., Deleuil, M., Demangeon, O. D. S., Demory, B. O., Ehrenreich, D., Erikson, A., Fossati, L., Fridlund, M., Futyan, D., Gandolfi, D., Gillon, M., Guedel, M., Heng, K., Isaak, K. G., Kiss, L., Laskar, J., Lecavelier des Etangs, A., Lendl, M., Lovis, C., Magrin, D., Maxted, P. F. L., Mecina, M., Mustill, A. J., Nascimbeni, V., Olofsson, G., Ottensamer, R., Pagano, I., Pallé, E., Peter, G., Piotto, G., Plesseria, J. Y., Pollacco, D., Queloz, D., Ragazzoni, R., Rando, N., Rauer, H., Ribas, I., Santos, N. C., Scandariato, G., Ségransan, D., Silvotti, R., Simon, A. E., Smith, A. M. S., Steller, M., Szabó, G. M., Thomas, N., Udry, S., Viotto, V., Walton, N. A., Westerdorff, K. and Wilson, T. G. (2021) A search for transiting planets around hot subdwarfs. I. Methods and performance tests on light curves from *Kepler*, K2, TESS, and CHEOPS. Astronomy & Astrophysics, 650, A205. https://doi.org/10.1051/0004-6361/202140381.

Vanderburg, A., Rappaport, S. A., Xu, S., Crossfield, I. J. M., Becker, J. C., Gary, B., Murgas, F., Blouin, S., Kaye, T. G., Palle, E., Melis, C., Morris, B. M., Kreidberg, L., Gorjian, V., Morley, C. V., Mann, A. W., Parviainen, H., Pearce, L. A., Newton, E. R., Carrillo, A., Zuckerman, B., Nelson, L., Zeimann, G., Brown, W. R., Tronsgaard, R., Klein, B., Ricker, G. R., Vanderspek, R. K., Latham, D. W., Seager, S., Winn, J. N., Jenkins, J. M., Adams, F. C., Benneke, B., Berardo, D., Buchhave, L. A., Caldwell, D. A., Christiansen, J. L., Collins, K. A., Colón, K. D., Daylan, T., Doty, J., Doyle, A. E., Dragomir, D., Dressing, C., Dufour, P., Fukui, A., Glidden, A., Guerrero, N. M., Guo, X., Heng, K., Henriksen, A. I., Huang, C. X., Kaltenegger, L., Kane, S. R., Lewis, J. A., Lissauer, J. J., Morales, F., Narita, N., Pepper, J., Rose, M. E., Smith, J. C., Stassun, K. G. and Yu, L. (2020) A giant planet candidate transiting a white dwarf. Nature, 585(7825), 363–367. https://doi.org/10.1038/s41586-020-2713-y.

Wilson, T. G., Farihi, J., Gänsicke, B. T. and Swan, A. (2019) The unbiased frequency of planetary signatures around single and binary white dwarfs using *Spitzer* and *Hubble*. Monthly Notices of the Royal Astronomical Society, 487(1), 133–146. https://doi.org/10.1093/mnras/stz1050.