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A transit survey to search for planets around hot subdwarfs

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Abstract

Hot subdwarf stars are small post-red-giant-branch stars. To this day, no planets have been confirmed around them. In this document we present the first results of our analysis to quantify the presence of planets around hot subdwarfs by performing a wide transit survey using photometric data from the first part of the mission TESS. Our work shows an absence of transiting planets for the majority of these stars, but some display potentially interesting signals. These are now observed in our follow-up procedure. We also compute upper limits of the occurrence rates for planets around hot subdwarf stars from the numerous stars displaying no signal.

Keywords: Hot subdwarfs stars, exoplanet, transit method, TESS

Résumé

À la recherche de transits planétaires autour d'étoiles sous-naines chaudes Les sous-naines chaudes sont de petites étoiles post-géante-rouges. Actuellement aucune planète n'a pu être confirmée autours d'elles. Dans ce document nous présentons les premiers résultats de notre analyse visant à quantifier leur nombre via la recherche de transits planétaires dans les données photométriques de la mission TESS. Nous avons pu déterminer qu'une large partie de ces étoiles n'affiche aucun transit attribuable à une planète, néanmoins plusieurs signaux potentiels ont été identifiés. Ces signaux sont maintenant observés dans notre procédure de suivi. Grâce au grand nombre d'étoiles sans transits, nous avons calculé la borne haute des probabilités de présence de planètes autour des étoiles de type sous-naines chaudes.

Mots-clés : Étoiles sous-naines chaudes, exoplanètes, méthode des transits

1. Introduction

Planets have been found around the majority of all types of stars, from the cool M-dwarfs down to the old pulsars. But for hot subdwarf stars (hereafter sdOB stars), none could be confirmed. These stars are evolved post Red-Giant-Branch (RGB) stars. Their progenitors are solar-like stars with mass between 0.8 and 2.3 solar masses. The progenitor gives birth to the sdOB star by losing most of its envelope at the tip of the RGB. SdOBs are therefore the remnant core of a red giant star and display very hot temperatures, between 20000 and 80000 K, and have radii between 0.1 and 0.3 solar radius (Heber, 2016).

The small size of sdOB stars makes them perfect targets for the detection of transiting planets, as transits are deeper compared to regular post-RGB stars of the red clump, which are very large stars. Smaller bodies are detectable down to the size of the Earth, or even below for the best cases. SdOB stars are therefore great candidates to perform a wide transit survey to detect small close-orbiting planets in a post-RGB environment (Van Grootel et al., 2021).

Moreover, this particular type of star is short-lived, with a lifespan of around 100 million years. In such a short time, the probability to form second-generation planets is low, as well as for the inward migration of previously far-orbiting planets. Therefore the discovery of short-period planets around sdOB stars would suggest that the planet may have survived through the RGB while remaining close to the star, or even being engulfed in it.

The main goal of our study is to perform an analysis of all the sdOB stars already observed in space missions by searching for transits in their light curves. From the large amount of stars available, we will be able to precisely constrain the occurrence rates of planets around sdOB stars. This document summarises the results we obtained during the analysis of the sdOB stars observed in the cycle 1 of NASA's Transiting Exoplanet Survey Satellite (TESS) mission, that were presented during a talk at the sdOB10 conference in Liège. This work has also its own publication, Thuillier et al. (2022).

2. Method

We used photometric data the TESS mission, which has observed and continues to observe most of the sky. Its observations are divided into cycles and sectors. A cycle consists in the observation of one celestial hemisphere and lasts for about a year. The cycles are then divided into 13 to 16 sectors that are observed 27 days each, corresponding to two orbits of TESS. When observing, the TESS field of view extends from close to the celestial equator, up to the celestial pole. This means that stars near the poles are observed for almost one year continuously, and the ones near the equator only for 27 days. The primary mission consisted of the cycles 1 and 2 (respectively southern and northern hemispheres) and in its extended mission, TESS is continuing alternating between north and south, now in cycle 5 (southern hemisphere).

In this work, we mainly used the 2-minute cadence mode from the mission. We focused on data from the cycle 1, which consists of the 792 sdOB stars observed by TESS in the southern celestial hemisphere, between July 2018 and July 2019. We extracted the data from the Mikulski Archive for Space Telescopes (MAST) and then analysed it with our pipeline, Searching for Hints of Exoplanets fRom Lightcurves Of spaCe-based seeKers (SHERLOCK; Pozuelos et al., 2020). This pipeline cleans the light curve by applying detrends of different window sizes, before looking for transit-like shapes using our own adapted version of the TransiLeast-Squares (Hippke and Heller, 2019) package. For all our analysis with SHERLOCK we decided to use low detection thresholds to allow a maximum of potential signals to be considered, at the expense of a higher number of false positives. We performed several operations to detect and remove them in the next steps of the study.

SHERLOCK provides a wide range of information with the signal it detects. In the first part of the checking, SHERLOCK's output for each star was visually checked and ranked in terms of interest. Ranking was done namely with numerical parameters, such as the signal-to-noise ratio (SNR), or the signal-detection-efficiency (SDE) but also with visual aspects, such as transit shapes, among others. For each target displaying at least one potential signal we tried to recover it in an analysis of TESS's observations of the same star in its cycle 3. This part of the mission focused on the re-observation of the southern hemisphere, and therefore the vast majority of cycle 1 targets appear in it. If the potential signal detected in cycle 1 did not appear in cycle 3, we stopped the investigation for the corresponding target. But if it was seen independently in both cycle 1 and cycle 3 then we performed a vetting. This part was also done with SHERLOCK, with the Lightcurve Analysis Tool for Transiting Exoplanet (LATTE; Eisner et al., 2020) package. Signals passing this step were then prepared for follow-up observation with a precise fitting of the transits, again using SHERLOCK, that works with the module Allesfitter (Günther and Daylan, 2019, 2021) for this part.

Once the fitting done, we prepared observation plans with SHERLOCK's scheduler tool. The follow-up is done with the two TRAPPIST telescopes (TRAnsiting Planets and Planetes-Imals Small Telescope), and for rare cases with ESA's mission CHEOPS. This part is still ongoing at the time of writing.

With the results from our analysis, we derived the occurrence rates for planets around sdOB stars as function of the planet's radii and periods. To perform this we firstly inferred our detection capability by performing injection-and-recovery tests. These tests consist in injecting synthetic planets into real light curves and trying to recover them. Each time we injected a planet, we gave it known properties such as its radius and period, and checked if our pipeline was able to recover it. By doing this a large number of times, we got a precise view of our detection capability. The tests were extensively performed for planets between 0.5 and 3 Earth radii and periods between 0.5 and 6 days. Few more tests were done to explore wider ranges as periods of 15, 25 and 35 days. Then we computed the transit probability of planets that is fully constrained by geometry and given by the formula 1. For this very first estimation of the occurrence rates, we neglected the potential eccentricity of orbit of the planet which gave formula 2.

$$P_{\text{transit}} = \left(\frac{R_\star + R_p}{a}\right)\frac{1+e\sin(\omega)}{1-e^2} \quad , \tag{1}$$

$$P_{\text{transit}} = \frac{R_\star + R_p}{a} \quad , \tag{2}$$

The upper limit for the number of planets is then given by formula 3. C is the confidence level, fixed at 95% in this study, and N' is the number of targets in the sample multiplied by the transit probability and the detection probability.

$$f_{\max} = 1 - (1-C)^{\frac{1}{N'+1}} \quad , \tag{3}$$

3. Results

Among the 792 sdOB stars observed by TESS in its cycle 1, we identified 549 with no signal. Some others displayed a potential signal in cycle 1, that was not recovered in cycle 3. A few targets were displaying consistent signals in both cycles but were then ruled out during our vetting. These were mainly due to star-induced variations such as pulsations, or the presence of unseen stellar-mass companions, such as brown dwarfs or small white dwarfs. Altogether, only 27 signals (from 24 stars) were suitable for follow-up observations. So far no planet have been confirmed, although this work is still ongoing.

Here we present the first statistics obtained with the 549 targets where no signal have been found during the first stage of the analysis. From this absence of detection in this large collection of stars, we were able to compute the upper limit for the occurrence rates of planets around sdOB stars as function of the planet's radii and periods. For example, we were able to determine that there is at most only 30% sdOB stars that have a planet of more than 2 Earth radii and period below 6 days, at 95% confidence.

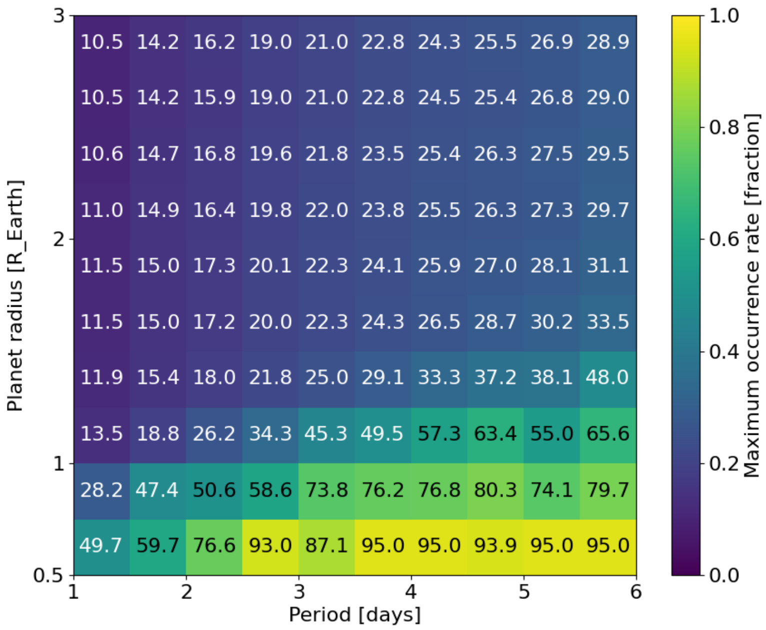

Figure 1: Upper limit for the occurrence rates of planets around hot subdwarf stars as a function of their radii and periods. Same as Fig. 6 of Thuillier et al. (2022) – CC BY 4.0.

Further Information

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Author contributions

AT performed the main analysis work, VVG and FP coordinated the project and focussed on the follow-up part. MDP and FP developed the SHERLOCK pipeline and continuously upgraded it. SC and LS helped studying peculiar targets with unexpected lightcurves.

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