Precise radial velocities of giant stars

XIV. Evidence of planetary companions around HD 25723, 17 Sco, 3 Cnc, and 44 UMa^{★,★★}

Marcelo Tala Pinto¹, Sabine Reffert¹, Andreas Quirrenbach¹, Stephan Stock¹, Trifon Trifonov³, and David S. Mitchell²

¹ Landessternwarte, Zentrum für Astronomie der Universität Heidelberg, Königstuhl 12, 69117 Heidelberg, Germany
e-mail: mtalapinto@protonmail.com

² Physics Department, California Polytechnic State University, San Luis Obispo, CA 93407, USA

³ Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

Received 28 April 2020 / Accepted 12 October 2020

ABSTRACT

Context. More than 100 exoplanets have been discovered around K and G giant stars, and their properties differ considerably from those of the planets found orbiting Sun-like and late-type main-sequence stars. This allows us to study the properties of planetary systems after the host star has evolved off the main-sequence, and it helps us to constrain planetary formation and evolution models.

Aims. Our aim is to find out whether the long-period radial velocity variations observed in four giant stars of the Lick survey are caused by orbiting planets, and to study the properties of the planet population as a function of the stellar evolutionary stage.

Methods. We analyzed 12 yr of precise radial velocity data for four stars of the Lick sample. In addition, we compared the planet frequency as a function of the evolutionary stage for two surveys, Lick and Express, based on the evolutionary stages derived using Bayesian inference.

Results. We report the discovery of two new exoplanets and three exoplanet candidates orbiting giant stars. The best Keplerian fits to the data yield minimum masses of $2.5 M_J$ and $4.3 M_J$ for the planets orbiting HD 25723 and 17 Sco, respectively. The minimum masses of an additional candidate around HD 25723, and of planet candidates around 3 Cnc and 44 UMa, would be $1.3 M_J$, $20.7 M_J$, and $12.1 M_J$, respectively. In addition, we compute planet frequencies for the Lick and Express samples as a function of the evolutionary stage. Within each sample, the planet frequency for the horizontal branch stars is the same as for the red giant branch stars.

Conclusions. We have discovered two new exoplanets and three new exoplanet candidates, one of them being the second planet in a possible multi-planetary system. Based on our derived planet frequencies, we conclude that stellar evolution does not affect the number of observable planets between the red-giant and horizontal-branch evolutionary stages.

Key words. techniques: radial velocities – planetary systems – planets and satellites: detection – brown dwarfs – stars: evolution

1. Introduction

Since the detection of the first exoplanet orbiting a K giant star (Frink et al. 2002), about 120 planets around G and K giant stars have been discovered using the radial velocity (RV) method. From that moment on, many surveys have searched for planets around these stars (Setiawan et al. 2003; Döllinger et al. 2007; Johnson et al. 2007; Sato et al. 2008a; Niedzielski & Wolszczan 2008; Wittenmyer et al. 2011; Jones et al. 2011; Lee et al. 2012). These discoveries were possible mainly because intermediate mass stars on the giant branch are cool and have many spectral lines and small rotation velocities, making them ideal targets for exoplanet searches using the RV method. In contrast, massive main-sequence stars have fewer spectral lines and higher rotation velocities, making it harder to measure precise radial velocities to detect exoplanets. The discovery of planets orbiting giant stars is essential as it allows us to probe the effects of stellar evolution on planetary systems and to test planetary formation theories in the intermediate mass regime ($1\text{--}3 M_\odot$).

However, photometric variations, coupled with stellar rotation, can distort stellar spectral line profiles, resulting in a spurious Doppler shift (Hatzes 2002). Furthermore, giant stars are known to pulsate, displaying several solar-like oscillation modes at different frequencies and with different amplitudes (Hatzes & Cochran 1993; Bedding et al. 2011; Wood 2015). When a star pulsates, parts of the stellar surface move toward the observer, while others move away, affecting the shape of the spectral lines and introducing a shift in the RV measurements. However, radial pulsation periods in giant stars are usually of the order of a few hours to a few days (e.g., Hatzes & Cochran 1995; De Ridder et al. 2006), and thus cannot be mistaken for periods of planets orbiting giant stars, which are typically of the order of 1–2 yr.

Hence, the interpretation of precise radial velocities of G and K giant stars can be ambiguous at times, as the recent examples of γ Draconis (Hatzes et al. 2018) and Aldebaran (Hatzes et al. 2015; Farr et al. 2018; Reichert et al. 2019) have shown. For both K giants the periodic radial velocity signal remained stable over many years, but later disappeared and apparently came back with a phase shift, which is inconsistent with the signal being due to an orbiting planet. Similarly, Delgado Mena et al. (2018) presented evidence for a correlation of radial velocities with the full width at half maximum of the inverse slope of the

* Tables B.1–B.4 are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/644/A1>

** Based on observations collected with the CAT telescope at the Lick Observatory, University of California, USA.

Table 1. Stellar parameters.

Parameter	HD 25723	17 Sco	3 Cnc	44 UMa
HIP ⁽¹⁾	19 011	79 540	39 177	53 261
Spectral type ⁽¹⁾	K1 III	K3 III	K3 III	K3 III
Evol. stage ⁽⁴⁾	HB (77%)	RGB (56%)	HB (86%)	HB (94%)
m_V (mag) ⁽¹⁾	5.62	5.24	5.60	5.12
$B - V$ (mag) ⁽¹⁾	1.06 ± 0.02	1.39 ± 0.01	1.32 ± 0.02	1.36 ± 0.01
Parallax (HIP2) (mas) ⁽²⁾	8.48 ± 0.37	8.62 ± 0.35	4.11 ± 0.51	4.99 ± 0.33
Distance (pc) ⁽²⁾	$117.9^{+5.38}_{-4.93}$	$116.0^{+4.91}_{-4.53}$	$243.3^{+34.46}_{-26.86}$	$200.4^{+14.19}_{-12.43}$
m_G (mag) ⁽³⁾	5.290 ± 0.001	4.701 ± 0.004	5.173 ± 0.002	4.622 ± 0.002
Parallax (<i>Gaia</i>) (mas) ⁽³⁾	8.68 ± 0.10	7.98 ± 0.16	4.00 ± 0.15	5.76 ± 0.12
Luminosity ($L_\odot$) ⁽⁴⁾	$87.99^{+6.10}_{-5.57}$	$179.62^{+11.10}_{-9.55}$	$478.82^{+97.95}_{-76.70}$	$569.56^{+56.27}_{-53.70}$
Mass ($M_\odot$) ⁽⁴⁾	$2.12^{+0.41}_{-0.55}$	$1.22^{+0.13}_{-0.14}$	$2.94^{+0.36}_{-0.33}$	$2.19^{+0.10}_{-0.43}$
Radius ($R_\odot$) ⁽⁴⁾	$13.76^{+0.56}_{-0.56}$	$25.92^{+0.78}_{-0.74}$	$39.38^{+3.68}_{-3.31}$	$45.12^{+1.97}_{-2.32}$
T_{eff} (K) ⁽⁴⁾	4766^{+49}_{-38}	4157^{+11}_{-10}	4319^{+24}_{-22}	4215^{+12}_{-13}
Age (Gyr) ⁽⁴⁾	$0.95^{+0.59}_{-0.25}$	$5.13^{+2.12}_{-1.33}$	$0.43^{+0.22}_{-0.12}$	$1.05^{+0.50}_{-0.18}$
$\log g$ (cm s ⁻²) ⁽⁴⁾	$2.50^{+0.10}_{-0.07}$	$1.70^{+0.04}_{-0.06}$	$1.71^{+0.06}_{-0.06}$	$1.46^{+0.04}_{-0.06}$
[Fe/H] (dex) ⁽⁵⁾	-0.03 ± 0.10	-0.01 ± 0.10	0.06 ± 0.10	-0.21 ± 0.10
$v \sin i$ (km s ⁻¹) ⁽⁵⁾	3.66 ± 1.40	3.98 ± 1.11	5.73 ± 0.94	3.61 ± 1.20
Rot. period (upper limit) (d)	190.21 ± 73.17	329.49 ± 92.40	347.70 ± 64.66	632.04 ± 212.24

Notes. Uncertainties refer to the 68% credibility interval.

References. ⁽¹⁾HIP, [Perryman et al. \(1997\)](#), ⁽²⁾HIP2, [van Leeuwen \(2007\)](#), ⁽³⁾*Gaia* DR2, [Gaia Collaboration \(2018\)](#), ⁽⁴⁾[Stock et al. \(2018\)](#), ⁽⁵⁾[Hekker & Meléndez \(2007\)](#).

cross-correlation bisector function for three K giant stars in open clusters, two of which had previously been considered planet hosts ([Lovis & Mayor 2007](#)). These studies show that one must be extremely careful when claiming exoplanet detections around these stars, especially for the more evolved stars with relatively large luminosities and radii, or late K spectral types.

In our Lick sample, we identified confirmed planets around eight stars so far ([Frink et al. 2002](#); [Reffert et al. 2006](#); [Mitchell et al. 2013](#); [Trifonov et al. 2014](#); [Ortiz et al. 2016](#); [Quirrenbach et al. 2019](#); [Luque et al. 2019](#)), while planets around five stars in our sample were found by other groups ([Sato et al. 2007, 2012](#); [Liu et al. 2008](#); [Wittenmyer et al. 2016](#); [Takarada et al. 2018](#)). In addition, we found many more stars with clearly periodic RVs, but whether the observed RV periodicities are really due to orbiting planets is a subject for further studies. We present the discovery of two new exoplanets and three planet candidates from the Lick sample. Additionally, we provide a study of the Lick and Express planet population as a function of the evolutionary stage of the host star.

The paper is organized as follows. In Sect. 2, we discuss our observations. In Sect. 3, we present stellar parameters of the stars under study, and in Sect. 4 we present the orbital parameters for the planetary systems. We provide a discussion of our results in Sect. 5 and compare the planet frequencies in the Lick and Express ([Jones et al. 2011](#)) samples as a function of the stellar evolutionary stage. In Sect. 5, we summarize our results.

2. Observations and stellar parameters

The RV measurements were obtained using the Hamilton Echelle Spectrometer (HES; [Vogt 1987](#)) fed by the 0.6 m Coudé Auxiliary Telescope (CAT) at the Lick Observatory, equipped

with an iodine cell to measure precise radial velocities ([Butler et al. 1996](#)). We collected 12 yr of data for our full sample of K and G giant stars, of which the four stars presented here are members. The resulting RV measurements have a median precision of 6.5 m s⁻¹ for HD 25723, 5.4 m s⁻¹ for 17 Sco, 6.2 m s⁻¹ for 3 Cnc, and 5.7 m s⁻¹ for 44 UMa. Errors in the RV measurements correspond to internal errors, namely photon-limited and calibration errors ([Butler et al. 1996](#)). Giant stars have larger RV jitter (due to solar-like oscillations) than main-sequence stars. These are of the order of 10–20 m s⁻¹ or larger, depending on the individual star ([Hekker et al. 2006](#)), so better RV precision would not significantly increase the detection threshold of a planetary signal.

The main stellar parameters of the four stars discussed in this paper are listed in Table 1. Magnitudes and trigonometric parallax measurements are available from both HIPPARCOS and *Gaia* DR2. The *Gaia* values are more precise for the four stars listed here, but this is not generally true for all stars in the Lick survey (stars brighter than 4.5 mag have typically more precise astrometry in HIPPARCOS); for consistency, the stellar parameters for the Lick sample in [Stock et al. \(2018\)](#) are based on the HIPPARCOS values. Spectroscopic metallicities and projected rotational velocities were determined by [Hekker & Meléndez \(2007\)](#). [Stock et al. \(2018\)](#) derived masses, radii, ages, surface gravities, effective temperatures, luminosities, and evolutionary stages for 372 stars of the Lick sample by comparing spectroscopic, photometric, and astrometric observables to grids of stellar evolutionary models using Bayesian inference. This methodology includes the initial mass function and evolutionary timescales of the stars as a prior. [Stock et al. \(2018\)](#) found that of the 372 stars in the Lick sample, 70 (19%) are more likely on the red giant branch (RGB), while the remaining 302 (81%)

Table 2. Orbital parameters.

Parameter	HD 25723 b	HD 25723 c	17 Sco b	3 Cnc b	44 UMa b
P (d)	$457.01^{+1.29}_{-1.31}$	$2273.17^{+151.11}_{-116.33}$	$578.38^{+2.01}_{-2.09}$	$853.64^{+4.76}_{-4.73}$	$785.74^{+4.80}_{-4.77}$
T_0 (JD – 2 450 000)	$1455.13^{+44.57}_{-70.82}$	$2324.28^{+341.59}_{-244.30}$	$3294.41^{+174.23}_{-182.91}$	$3806.70^{+227.01}_{-175.74}$	$3560.34^{+98.94}_{-90.81}$
e	$0.04^{+0.05}_{-0.03}$	$0.34^{+0.20}_{-0.17}$	$0.06^{+0.03}_{-0.02}$	$0.04^{+0.04}_{-0.03}$	$0.11^{+0.06}_{-0.05}$
ω (deg)	$112.97^{+55.83}_{-44.06}$	$249.59^{+34.08}_{-53.16}$	$57.03^{+113.18}_{-106.77}$	$275.18^{+73.58}_{-96.04}$	$135.60^{+40.66}_{-45.59}$
$a_1 \sin i$ (AU)	$1.68^{+0.04}_{-0.05} \times 10^{-3}$	$2.64^{+0.22}_{-0.20} \times 10^{-3}$	$4.90^{+0.08}_{-0.08} \times 10^{-3}$	$1.69^{+0.04}_{-0.03} \times 10^{-2}$	$1.14^{+0.03}_{-0.04} \times 10^{-2}$
K (m s $^{-1}$)	$40.03^{+2.40}_{-2.42}$	$13.41^{+2.84}_{-2.59}$	$92.40^{+3.90}_{-3.84}$	$216.07^{+11.15}_{-11.16}$	$158.74^{+8.55}_{-8.62}$
$m \sin i$ (M_J)	$2.50^{+0.14}_{-0.17}$	$1.34^{+0.08}_{-0.11}$	$4.32^{+0.15}_{-0.12}$	$20.76^{+0.72}_{-0.73}$	$12.11^{+0.20}_{-0.85}$
a (AU)	$1.49^{+0.04}_{-0.05}$	$4.35^{+0.22}_{-0.03}$	$1.45^{+0.02}_{-0.02}$	$2.52^{+0.03}_{-0.04}$	$2.16^{+0.02}_{-0.06}$
$f(m)$ ($M_\odot$)	$3.03^{+0.06}_{-0.06} \times 10^{-9}$	$4.70^{+0.07}_{-0.06} \times 10^{-10}$	$4.70^{+0.09}_{-0.10} \times 10^{-8}$	$9.01^{+0.18}_{-0.23} \times 10^{-7}$	$3.19^{+0.06}_{-0.08} \times 10^{-7}$
Stellar jitter (m s $^{-1}$) (fixed)	13.39		28.95	58.11	43.11
Reduced χ^2	0.98		1.06	1.09	1.08

are probably on the horizontal branch (HB). Three of the stars presented here are on the HB – HD 25723, 3 Cnc, 44 UMa –, all with probabilities greater than 75%, while only 17 Sco is more likely (56%) on the RGB. Thus, the evolutionary stage of 17 Sco is relatively uncertain. For the HB stars, the masses are $2.12^{+0.41}_{-0.55} M_\odot$, $2.94^{+0.36}_{-0.22} M_\odot$, and $2.19^{+0.10}_{-0.43} M_\odot$ for HD 25723, 3 Cnc and 44 UMa, respectively. If they were on the RGB instead, the masses of HD 25723 and 3 Cnc would not change considerably, while the mass of 44 UMa would be only $1.74^{+0.05}_{-0.07} M_\odot$. The mass of 17 Sco is $1.22^{+0.13}_{-0.14} M_\odot$ if on the RGB and only $0.88^{+0.17}_{-0.01} M_\odot$ if on the HB.

As can be seen, 3 Cnc and 44 UMa are slightly more evolved than the other two stars, with radii of about 40–45 $R_\odot$ and luminosities around 500 $L_\odot$. Those are the two stars whose potential companions we label as planet candidates, because of the more evolved stage, and consequently higher RV jitter, of their host stars.

Of the 373 stars in the Lick survey, only 217 have *Gaia* parallaxes. Adopting these instead of the HIPPARCOS parallaxes changes the estimated evolutionary stage for only about 2% of these 217 stars. In general, the parallaxes are not expected to have a dominant influence on the evolutionary stage determination (Stock et al. 2018). Therefore, we used the evolutionary stages based on the HIPPARCOS data.

3. Planetary orbits and intrinsic stellar effects

We fit Keplerian orbits to the RV data via χ^2 minimization. For each orbital solution, five parameters were fit: the orbital period P , the periastron time T_0 , the longitude of the periastron ω , the orbital eccentricity e , and the semi-major axis of the stellar orbit $a_1 \sin i$. The RV offset to which the orbits are referred is zero by definition. Uncertainties in the fit and derived parameters K , a , $m \sin i$, and $f(m)$ were computed using the affine-invariant Markov chain Monte Carlo (MCMC) Sampler¹ (Goodman & Weare 2010). All of the fit and derived parameters are included in Table 2.

As an alternative, we also fit Keplerian orbits to the RV data using the Bayesian approach as opposed to the frequentist approach, which has the advantage that one can also fit for stellar jitter (as opposed to assuming a fixed value). All derived orbital

parameters were the same within their errors, and the errors on the orbital parameters were also almost identical. We conclude that at least for strong RV signals it does not matter which kind of fitting is employed.

In the case of HD 25723, to further constrain the hypothesis of the second planet candidate, we performed a detailed dynamical analysis of the two-planet system. For this purpose, we employed the *exostriker* exoplanet modeling toolbox (Trifonov 2019), and we followed a route similar to that of Trifonov et al. (2019). Using the MCMC sampler *emcee* (Foreman-Mackey et al. 2013), in conjunction with the dynamical modeling scheme integrated in the *exostriker*, we constructed MCMC parameter posteriors and studied their dynamical behavior. We integrated each individual MCMC sample for 100 kyr with a time step of 1 d, and we evaluated the overall stability and dynamical properties of this candidate two-planet system (for more details on the dynamical analysis setup, see Trifonov et al. 2019).

We also evaluated the possibility of measuring the planetary signals astrometrically. The amplitude of the expected astrometric motion due to these companions is 0.03 mas, 0.08 mas, 0.14 mas, and 0.13 mas for HD 25723, 17 Sco, 3 Cnc and 44 UMa, respectively. The precision of the fit astrometric parameters from HIPPARCOS and *Gaia* DR2 for these stars is of the order of 0.2–0.4 mas and 0.1–0.2 mas, respectively. For 3 Cnc and 44 UMa, the final astrometric precision of *Gaia* might be sufficient to confirm or disprove the presence of the putative companions, and possibly also to determine the orbital inclination and thus the companion mass.

3.1. Intrinsic stellar effects

In addition to planetary or stellar companions, there are intrinsic stellar sources of RV variability that complicate the detection of substellar companions. In this section, we describe the methods we used to estimate the RV variations due to stellar rotation and radial pulsations, while the results of these estimations for each star are presented in Sect. 3.2.

3.1.1. Rotational modulation

Although giant stars show only a very small level of photometric variability during the RGB and HB evolutionary stages, we

¹ https://github.com/mcfit/idl_emcee

Fig. 1. Radial velocity curve for HD 25723. *Top panel:* RV data with best Keplerian fit. *Bottom panel:* RV residuals after subtraction of the best fit.

Fig. 2. Phase-folded radial velocity curve for HD 25723. RV data with best Keplerian fit.

investigate here whether intrinsic stellar phenomena in combination with stellar rotation could possibly be responsible for the periodic RV variations that we observe.

Based on the value of the projected rotational velocity and the stellar radius listed in Table 1, an upper limit for the rotation period can be calculated as $P_{\max} = 2\pi R_*/(v \sin i)$. To test if the observed RV signals are due to rotational modulation of surface features, we compare the observed period in the RV time series with the maximum rotational period of the star.

Hatzes (2002) made predictions for the spot filling factor as a function of the projected rotational velocity and the amplitude of

Fig. 3. GLS periodograms for HD 25723 of RV data, residuals after subtraction of the best fit, $H\alpha$ index, window function, HIPPARCOS, and ASAS SN V-band and TESS photometry. The blue dashed line corresponds to the orbital period of the planet. The green dashed line corresponds to the upper limit of the stellar rotation period. The green area shows the minimum and maximum value that the upper limit of the stellar rotation period can have, given its uncertainty. The gray vertical dashed lines correspond to one month (29.53 d) and one year (365.25 d) periods. The purple dashed lines in the RV data GLS show the yearly aliases of the main peak. The horizontal red lines show the 10%, 5% and 1% FAP levels. The gray line in the residuals of the two Keplerian solution shows the residual GLS of one Keplerian plus linear trend solution. The gray line in the residual GLS of the one Keplerian solution shows the residuals GLS of one Keplerian solution modeled with the orbital parameters of the double-Keplerian solution.

the observed RV signal. Given a spot filling factor, we can predict the photometric variations expected due to spots and compare these with the observed photometric variability to see whether this is a viable scenario for a particular star.

In addition, we looked for periodicities in the HIPPARCOS (Perryman et al. 1997) and ASAS SN (Shappee et al. 2014; Kochanek et al. 2017) V-band photometric time series, shown in Fig. A.1. Moreover, TESS (Ricker et al. 2015) data, shown in Fig. A.2, are available for two of these stars, HD 25723 and 44 UMa; however, the timescale of the TESS observations does not cover a significant part of the rotation period of the star. We analyzed TESS data separately, as the bandwidth of its observations is much broader than that of HIPPARCOS and ASAS SN.

3.1.2. $H\alpha$ index

The inhomogeneity of the spot distribution on the stellar surface, modulated with the stellar rotation period, can produce periodic changes in the shape of stellar spectral lines and thus induce RV variations with the rotation period. Therefore, we searched for periodicities in the time series of the $H\alpha$ indices in order to compare them with the periods observed in the RVs. The $H\alpha$ indices of the Lick stars were derived by Staudt (2020), based

Table 3. Orbital parameters of the HD 25723 planetary system.

Orb. param.	MCMC samples		<i>N</i> -body solution		Stable solution	
	HD 25723 b	HD 25723 c	HD 25723 b	HD 25723 c	HD 25723 b	HD 25723 c
<i>P</i> (days)	456.91 ^{+1.78} _{-1.40}	2323.54 ^{+196.31} _{-62.17}	456.52	2289.21	456.78	2369.84
<i>K</i> (m s ⁻¹)	40.05 ^{+2.54} _{-2.48}	12.68 ^{+2.63} _{-2.47}	40.69	13.90	40.09	13.59
<i>e</i>	0.02 ^{+0.08} _{-0.01}	0.22 ^{+0.18} _{-0.14}	0.04	0.28	0.05	0.22
ω (deg)	75.88 ^{+73.83} _{-34.91}	210.9 ^{+38.04} _{-63.86}	70.52	253.21	89.48	210.58
<i>M</i> (deg)	143.82 ^{+39.97} _{-68.82}	60.22 ^{+64.16} _{-39.23}	153.79	11.44	134.73	12.43
σ_{jitter} (m s ⁻¹)	13.21 ^{+1.77} _{-1.40}		13.38		13.22	
RV offset (m s ⁻¹)	-2.35 ^{+1.86} _{-1.95}		-2.08		-2.24	
<i>m</i> sin <i>i</i> (<i>M_J</i>)	2.49 ^{+0.11} _{-0.17}	1.31 ^{+0.08} _{-0.13}	2.55	1.34	2.51	1.33
<i>a</i> (AU)	1.49 ^{+0.04} _{-0.05}	4.35 ^{+0.11} _{-0.12}	1.49	4.37	1.49	4.35

Notes. The first column shows the mode of the dynamical MCMC samples and the 68% confidence interval as an error bar. The second column shows the best dynamical fit, while the third column shows the best stable fit. All fits are fixed to be edge-on and coplanar.

on the definition of [Boisse et al. \(2009\)](#). During the survey, several CCD detectors were used, and although the radial velocities themselves are insensitive to the particular detector choice, the H α indices are not, introducing an offset in the time series of the H α indices whenever the detector was changed. In order to account for this, we have determined the mean H α index for each detector and star and adjusted the data for the corresponding offsets. The time series of the offset-adjusted H α indices are shown in Fig. A.3.

3.1.3. Radial pulsations

Using the scaling relations from [Kjeldsen & Bedding \(2011\)](#), we estimated the amplitude of the RV variations due to solar-like radial pulsations and compared it to the observed RV jitter (residuals to the Keplerian fit).

3.2. RV analysis

3.2.1. HD 25723

The time series of the 107 RV measurements of HD 25723 is shown in Fig. 1, along with the best double-Keplerian fit to the data. The lower panel shows the residual RV data, after subtraction of this fit. Figure 2 shows the phase-folded RV measurements, along with the best Keplerian fit. The RV variations are clearly periodic, with a very significant peak in the Generalized Lomb-Scargle (GLS) periodogram ([Zechmeister & Kürster 2009](#)), which is shown in Fig. 3, and for which the Keplerian orbit solution yields a period of about 457 d. The best fit orbital parameters are listed in Table 2.

There is a second marginally significant peak in the periodogram of the original data, shown in Fig. 3, at a period of about 202 d, which corresponds to the yearly alias of the 457-day peak and vanishes in the periodogram of the residuals. There are two further peaks in the periodogram of the residuals at 10.5 d and at 2430 d (~ 6.5 yr) in the one-Keplerian solution GLS, but they are not significant at the 1% false alarm probability (FAP) level. The 2430-day period corresponds roughly to a yearly alias of the 457-day period, although it does not completely vanish after removal of the main signal.

The trend observed in the residuals may indicate the presence of a second companion. Therefore, we additionally fit a double

Keplerian model and a single Keplerian with a linear trend to the RV data. The double Keplerian solution yields a period of 457 d for the main planet and 2273 d for the second planet, and $\chi^2_{\text{red}} = 0.99$. The single Keplerian plus linear trend solution yields a slope of about $-1.65 \pm 0.46 \text{ m s}^{-1} \text{ yr}^{-1}$ and $\chi^2_{\text{red}} = 0.99$. The *F*-test favors the single Keplerian plus linear trend over the double Keplerian model. In contrast, the Bayesian information criterion (BIC) favors the double Keplerian model over the single Keplerian plus trend with $\Delta\text{BIC} = 10.1$, just above the significance threshold according to this test. Although we observe a signal in the data, the evidence in favor of the planetary hypothesis is not fully secure. We require a substantial amount of additional RV data to provide confirmation. Hence, we prefer to label HD 25723 c as a planet candidate. We do not observe any significant periodicities in the residuals of the double-Keplerian solution, nor in the residuals of the single Keplerian plus linear trend solution, which is shown in gray in the GLS periodogram of the double-Keplerian residuals for comparison (see Fig. 3). The best fit orbital parameters are listed in Table 2.

As an additional test, we modeled the orbit of the dominant planet using the orbital parameters of the double-Keplerian solution. The GLS of the residuals of this model is shown in gray in the single-planet residuals in Fig. 3. The peak at about 2430 d increases its significance with respect to the single-Keplerian solution, arising over the 5% FAP, providing additional evidence in favor of the two-planet hypothesis.

If one assumes that star spots are the cause of the observed RV variations, then the rotation period of the star must coincide with the period of the RV data within the errors. The upper limit of the stellar rotation period is about 190 d. This period is not consistent with the 457-day period observed in the RV data, nor with the 2430-day period observed in the residuals of the single-Keplerian fit.

Furthermore, there is no significant periodicity in the H α variation time series, nor in the HIPPARCOS, ASAS SN, or TESS photometry, at the orbital period predicted by the Keplerian orbit, as shown in Fig. 3. We observe a significant peak at 366 d in the H α index periodogram, which is very close to 1 year and is probably due to the sampling, as the peak also appears in the window function. Hence, we conclude that rotational modulation is probably not the primary source of the RV variability observed in HD 25723.

Fig. 4. Semi-major axes, eccentricities, and period ratio evolution of the best dynamical fit for 50 000 yr.

The mean precision of the RV measurements is 6.51 m s^{-1} , smaller than the actual 16.70 m s^{-1} rms of the residuals. The stellar jitter derived by quadratically subtracting the mean of the observational errors from the rms of the residuals is 13.39 m s^{-1} . This is fully consistent with the 15.13 m s^{-1} amplitude of solar-like oscillations predicted with the scaling relations from [Kjeldsen & Bedding \(2011\)](#).

The dynamical solution and orbital evolution. We used the orbital elements of the best double-Keplerian fit as a first guess for the dynamical fit. We adopted a coplanar and edge-on configuration for this system (i.e., $i_{b,c} = 90^\circ$, $\Omega_{b,c} = 0^\circ$), for consistency with the unperturbed double-Keplerian model. We observe no significant differences between the double-Keplerian and the N -body orbital solutions. The values of the orbital elements, with their corresponding uncertainties, of both solutions are in mutual agreement, as shown in Tables 2 and 3. This is expected, as the two Jovian planets are too separated to influence each other's orbits on short timescales. However, as our intention is to study the long-term stability of the HD 25723 planetary system for coplanar edge-on configurations, the orbital evolution computation is based on the dynamical model.

The MCMC analysis provides a median solution that is in agreement with the best dynamical fit and with the best double-Keplerian fit. The orbital evolution of the best coplanar edge-on dynamical fit, shown in Fig. 4, shows that the system is long-term stable and locked in a 5:1 mean motion resonance (MMR). Figure 16 shows the posterior distribution of the orbital parameters using a dynamical, edge-on, co-planar model. The stable samples are shown in black and the non-stable samples are shown in red. Of the total number of samples, only 5.7% are not stable, and they correspond to those in which $e_c > 0.46$. The

orbital parameters of the best dynamical and stable solutions are listed in Table 3.

3.2.2. 17 Sco

We measured 121 RVs for this star, which are shown in Fig. 5 together with the best Keplerian fit to the data. The lower panel shows the RV residuals after subtraction of the best fit. Figure 6 shows the phase-folded RV measurements, along with the best Keplerian fit. The GLS periodogram (Fig. 7) shows a very clear and strong peak at $\sim 577 \text{ d}$, a second peak at $\sim 222 \text{ d}$, and a third, less significant peak at $\sim 990 \text{ d}$. The second and third peaks correspond to yearly aliases of the period of the main peak. After the removal of the best Keplerian fit, no prominent peaks remain in the periodogram of the RV residuals. The full set of orbital parameters is listed in Table 2.

The upper limit of the rotation period of 17 Sco, calculated from the values in Table 1, is about 329 d (i.e., smaller than the period of the companion). The rms of the Keplerian fit is 29.52 m s^{-1} , which leads to a contribution from stellar RV jitter of about 28.95 m s^{-1} . This additional jitter is much smaller than the 126 m s^{-1} expected from the scaling relations from [Kjeldsen & Bedding \(2011\)](#). Recently, [Müller \(2019\)](#) investigated how well the scaling relations from [Kjeldsen & Bedding \(2011\)](#) actually predict the observed stellar jitter in the Lick sample. It turns out that especially for effective temperatures below 4400 K and/or $\log g < 2$, there are considerable mismatches, often larger than 50 m s^{-1} . In our sample, this concerns mostly RGB stars of roughly one solar mass, of which 17 Sco is an example.

We find no significant periodicity in the $H\alpha$ index, nor in the HIPPARCOS+ASAS SN photometry, at the orbital period of the companion, as shown in Fig. 7. However, there is a weak period in the $H\alpha$ index periodogram close to the orbital period. To investigate the coherence of this signal, we computed the stacked Bayesian Lomb-Scargle periodogram (sBGLS; [Mortier & Collier Cameron 2017](#)). Figure 8 shows the sBGLS periodogram of the RV data and of the $H\alpha$ index. One would expect the signals observed in the RV data to be correlated with the signals observed in the $H\alpha$ index in the case of a stellar activity cycle. In the RV data sBGLS periodogram, the planetary signal remains stable at the orbital period, with a significance that increases with the number of observations, while in the $H\alpha$ sBGLS, the highest peak appears first at about 390 d, then it shifts to about 610 d, it goes up to 700 d, ending up at about 625 d. Hence, most likely the periodicity we observe in the RV data at 457 d is not related to the variations of the $H\alpha$ index.

3.2.3. 3 Cnc

We measured 67 RVs for 3 Cnc, shown in Fig. 9, along with the best Keplerian fit to the data. The lower panel shows the RV residuals, after subtraction of the best fit. Figure 10 shows the phase-folded RV measurements, along with the best Keplerian fit. The periodogram, shown in Fig. 11, reveals a strong peak at 857 d. The best Keplerian fit has a period of $\sim 853 \text{ d}$. The complete set of orbital parameters is listed in Table 2.

Figure 11 shows the periodogram of the residuals, after subtraction of the best fit. We find a significant peak at 1 d, which corresponds to a daily sampling alias, and two peaks close to the 10% FAP at 211 and 1405 d. After subtracting the 1-day signal from the residuals, the peak at 211 d disappears, leaving only the peak at 1405 d. To test whether this peak corresponds to a planetary signal, we fit the RV data with a two-Keplerian model, using the 1405-day period as a first guess for the period of the

Fig. 5. Radial velocity curve for 17 Sco. *Top panel:* RV data with best Keplerian fit. *Bottom panel:* RV residuals after subtraction of the best fit.

Fig. 6. Phase-folded radial velocity curve for 17 Sco. RV data with best Keplerian fit.

second planet. An F -test suggests that a one-Keplerian model with a fixed jitter term provides a better description of the system. Hence, most likely the 1405-day peak in the residuals does not correspond to a planetary signal.

The amplitude of the variations in the HIPPARCOS photometry is about 1.5%, which is of the same order of magnitude as the expectations from the spot modeling tool SOAP2.0 (Dumusque et al. 2014) for three spots at different locations on the stellar surface. However, there are no significant photometric variations at the orbital period nor at any other periods, as shown in Fig. 11. Based on the projected rotational velocity and stellar radius, listed in Table 1, the projected rotation period is ≤ 348 d, which is significantly smaller than the orbital period of the planetary companion. Moreover, we find no periodicity in the $H\alpha$ index GLS, shown in Fig. 11, at the period of the RV variations. We therefore discarded rotational modulation as a likely cause for the observed RV variability.

The mean precision of the RV measurements is 6.34 m s^{-1} , which is considerably smaller than the actual 58.38 m s^{-1} rms of the post-fit residuals. The additional RV jitter is 58.11 m s^{-1} , which is broadly consistent with the 76.52 m s^{-1} amplitude of solar-like oscillations predicted from Kjeldsen & Bedding (2011).

3.2.4. 44 UMa

We obtained 68 RV measurements for 44 UMa. They are shown in Fig. 12, along with the best Keplerian fit to the data. The lower

Fig. 7. GLS periodograms for 17 Sco of RV data, residuals after subtraction of the best fit, $H\alpha$ index, window function, and HIPPARCOS and ASAS SN V-band photometry. The blue dashed line corresponds to the orbital period of the planet. The green dashed line corresponds to the upper limit of the stellar rotation period. The green area shows the minimum and maximum value that the upper limit of the stellar rotation period can have, given its uncertainty. The gray vertical dashed lines correspond to one-month (29.53 d) and one-year (365.25 d) periods. The purple dashed lines in the RV data GLS show the yearly aliases of the main peak. The horizontal red lines show the 10%, 5%, and 1% FAP levels.

Fig. 8. SBGLS periodogram for 17 Sco of RV data and $H\alpha$ index. The dashed vertical line corresponds to the orbital period of the planet.

panel shows the residuals of the RV data, after subtraction of the best fit. Figure 13 shows the phase-folded RV measurements, along with the best Keplerian fit. The periodogram (Fig. 14) reveals a strong peak at 791 d. The smaller, but still significant peak at ~ 246 d corresponds to a yearly alias. After removing the best Keplerian fit to the data, we see that there are no significant peaks in the periodogram of the RV residuals.

From the projected rotational velocity and the stellar radius, both listed in Table 1, we estimate a projected stellar rotation

Fig. 9. Radial velocity curve for 3 Cnc. *Top panel:* RV data with best Keplerian fit. *Bottom panel:* residual RV data after subtraction of the best fit.

Fig. 10. Phase-folded radial velocity curve for 3 Cnc. RV data with best Keplerian fit.

period of 632 d. Considering its uncertainty, the maximum rotation period is 844 d. This value is larger than the RV period; the RV variations could thus in principle be explained by star spots. We therefore estimated the spot filling factor and the resulting photometric variations due to the presence of spots. Based on [Hatzes \(2002\)](#), given the RV amplitude and the projected rotational velocity, the spot filling factor is 6.5%. SOAP2.0 predicts photometric variations of 5.0%, 3.1%, and 2.1% for two, three and four spots, respectively, for the calculated spot filling factor. The amplitude of the HIPPARCOS photometric variation is about 1.7% (see Fig. 14), which is broadly consistent with the SOAP2.0 expectations in the presence of a few (dominant) stellar spots. However, we do not see any periodicity in the GLS periodogram of the photometry, shown in Fig. 14, at the rotation period of the star. Moreover, we find no significant period at the orbital period of the companion candidate, nor at the rotation period of the star, in the $H\alpha$ index periodogram, shown in Fig. 14. Hence, most likely rotational modulation is not the source of the observed RV variations.

The observed contribution from stellar jitter to the RV residuals is 43.11 m s^{-1} , whereas the scaling relations from [Kjeldsen & Bedding \(2011\)](#) yield 157.24 m s^{-1} . Moreover, 44 UMa has an effective temperature below 4400 K and a $\log g < 2$; in this parameter range, [Müller \(2019\)](#) found large discrepancies between the simple scaling relation and observations.

Fig. 11. GLS periodograms for 3 Cnc of RV data, residuals after subtraction of the best fit, $H\alpha$ index, window function and HIPPARCOS and ASAS SN V-band photometry. The blue dashed line corresponds to the orbital period of the planet. The green dashed line corresponds to the upper limit of the stellar rotation period. The green area shows the minimum and maximum value that the upper limit of the stellar rotation period can have, given its uncertainty. The gray vertical dashed lines correspond to one-month (29.53 d) and one-year (365.25 d) periods. The purple dashed lines in the RV data GLS show the yearly aliases of the main peak. The horizontal red lines show the 10%, 5%, and 1% FAP levels.

4. Discussion

4.1. Substellar companions

Our analysis indicates that the most probable explanation for the observed periodicities in the RV time series of the stars presented here is the presence of planetary companions. The Keplerian fits indicate that these objects have the typical characteristics of giant planets around K giant stars – massive planets with orbital periods of several hundreds of days.

We examined the $H\alpha$ indices and the HIPPARCOS, ASAS SN, and TESS photometry and do not find any periodicities at the periods observed in the RVs. We must caution, though, that the photometric data were not taken simultaneously with the RV data and that the precision and cadence are not ideal for revealing low-amplitude photometric periodicities. However, the upper limits of the rotational periods of three of the stars are not consistent with the RV periodicities anyway (the exception being 44 UMa). Hence, it is most likely that the detected periods of several hundred days in our stars are due to planetary companions, not to intrinsic stellar effects. All five planetary orbits are relatively circular with semi-major axes ranging from 1.5 AU to 2.5 AU (the exception being HD 25723 c), as is common for giant planets orbiting giant stars ([Jones et al. 2014](#)).

According to the IAU (2003) definition, which invokes the minimum mass for deuterium burning as the distinction between giant planets and brown dwarfs, four of the substellar companions are in the giant planet regime, with minimum masses of $2.5 M_J$, $1.3 M_J$, $4.3 M_J$, and $12.1 M_J$ for HD 25723 b, HD 25723 c,

Fig. 12. Radial velocity curve for 44 UMa. *Top panel:* RV data with best Keplerian fit. *Bottom panel:* residual RV data after subtraction of the best fit.

Fig. 13. Phase-folded radial velocity curve for 44 UMa. RV data with best Keplerian fit.

17 Sco b, and 44 UMa b, respectively. The minimum mass of 3 Cnc b is $20.8 M_J$, so it should be considered a brown dwarf. However, in line with the suggestion by, for example, [Chabrier et al. \(2014\)](#), we refer to all substellar companions found in the Lick survey as giant planets, since they all fulfill the criterion of a rather large mass ratio between the host star and the companion. This definition appears in particular appropriate for the ν Oph system, where the two $22 M_J$ and $25 M_J$ companions have most likely formed in a disk ([Quirrenbach et al. 2019](#)), as indicated by their 6:1 resonance.

Including 3 Cnc b, there are four planets with (minimum) masses larger than $13 M_J$ among a total of 16 planets discovered in the Lick sample of 373 giant stars. Two of them orbit ν Oph ([Quirrenbach et al. 2019](#)), and the fourth is τ Gem b ([Mitchell et al. 2013](#)). The nominal frequency of planets with minimum mass larger than $13 M_J$ in the Lick sample is thus $1.1^{+1.4}_{-0.2}\%$, where the error bars were computed according to the beta distribution quantile technique as advocated by [Cameron \(2011\)](#). In the Express sample, the fraction of companions with masses larger than $13 M_J$ is $0.6^{+1.4}_{-0.2}\%$; only one companion, HIP 97233 b, with a mass of $20 M_J$, was detected in a sample of 166 stars ([Jones et al. 2015](#)). The two values are fully consistent with each other, given the small sample sizes and corresponding error bars. Moreover, the massive planet ($13 < M_P/M_J < 80$) occurrence rate within 2–3 AU around A and F stars ($M_* > 1.5 M_\odot$), the progenitors of

Fig. 14. GLS periodograms for 44 UMa of RV data, residuals after subtraction of the best fit, $H\alpha$ index, window function, HIPPARCOS, and ASAS SN V-band and TESS photometry. The blue dashed line corresponds to the orbital period of the planet. The green dashed line corresponds to the upper limit of the stellar rotation period. The green area shows the minimum and maximum value that the upper limit of the stellar rotation period can have, given its uncertainty. The gray vertical dashed lines correspond to one-month (29.53 d) and one-year (365.25 d) periods. The purple dashed lines in the RV data GLS show the yearly aliases of the main peak. The horizontal red lines show the 10%, 5%, and 1% FAP levels.

the evolved giants, is below 4% at the 1σ level ([Borgniet et al. 2019](#)), which is also in agreement with the above numbers.

4.2. Stellar oscillations

[Saio et al. \(2015\)](#) discussed oscillatory convective modes in red giants as an alternative explanation for long secondary periods of semi-regular variables. These oscillatory convective modes are nonadiabatic g -modes present in very luminous stars, such as red giants with $\log L/L_\odot \gtrsim 3$. Figure 15 shows the theoretical period-luminosity (PL) relation of these oscillatory convective modes for two mixing length parameters ($\alpha = 1.2, 1.9$), and for metal abundance $Z = 0.008$. It is not clear where these relations would lie for different abundances or slightly different stellar models, but it is worth pointing out that the relations computed by [Saio et al. \(2015\)](#) are rather close to the positions of 3 Cnc and 44 UMa.

Both 3 Cnc and 44 UMa are also located close to the positions of γ Dra, NGC 4349-127, and Aldebaran in the PL diagram. For those stars, it has recently been shown that they do not harbor planets, although on short timescales the RV variations appear periodic. On longer timescales, however, the RV pattern is not stable; there seem to be jumps in phase and/or period

Fig. 15. Period-luminosity relations of oscillatory convective modes with mixing length parameters of 1.9 (dashed lines) and 1.2 (solid lines), for stars with $1 M_{\odot}$ (blue), $1.3 M_{\odot}$ (red), and $2.0 M_{\odot}$ (green). All models are from [Saio et al. \(2015\)](#); they were computed for metal abundance $Z = 0.008$. The small gray circles are presumptive planets around giant stars gathered from the literature, the yellow and blue circles are the planets found in the Lick survey, the dark red circles are stars that show RV variability that is probably produced by stellar activity, and the yellow and blue stars are the new planets and planet candidates presented in this paper.

([Hatzes et al. 2018](#); [Reichert et al. 2019](#)). The luminosities of two other presumptive planet hosts in open clusters, IC 4651-9122 and NGC 2423-3 ([Delgado Mena et al. 2018](#)), are much lower. Considering their stellar parameters, and the period and amplitude of their observed RV variability, the presence of this type of pulsations seems to be less likely.

3 Cnc and 44 UMa have suspiciously similar stellar parameters to γ Dra and Aldebaran; all have radii in a relatively narrow range from 40–50 $R_{\odot}$, luminosities between 400 and 550 $L_{\odot}$, and $\log g < 2$, although 3 Cnc and 44 UMa are most likely already on the HB, whereas Aldebaran is probably still approaching the tip of the RGB. Given these similarities, we prefer to be cautious and to simply call 3 Cnc and 44 UMa candidate planet hosts. Confirmation of the two planet candidates would require dense RV monitoring over another 5–10 RV cycles, in order to ensure that they do not show any phase jumps or variations of the period, such as γ Dra and Aldebaran. We stress that it is not possible to confirm the planetary hypothesis by analyzing only the RVs. Additional information, for example about the stability of the line shapes, would be very valuable, but data from non-stabilized instruments such as the HES used in this work are poorly suited for that type of analysis. The position of the host stars in the PL diagram may also provide new insight into the reality of presumed giant star planets, as it can help to distinguish which ones are prone to oscillatory convective modes.

4.3. Evolutionary stages

Several studies have investigated the fate of planets after they evolve off the main sequence up the giant branch. Many of them predict that planetary systems will be subject to profound changes during the post-main-sequence evolution of their host stars, due to planet engulfment as the radius of the star increases ([Sato et al. 2008b](#)), or by changes in the orbital distance due to stellar mass loss or stellar tides ([Villaver et al. 2014](#); [Kunitomo et al. 2011](#)). In the following, we compare the planet frequency for the various stellar evolutionary phases in the Lick

and Express planet search samples, in order to investigate any possible effects of stellar evolution on the number of observable planets.

[Stock et al. \(2018\)](#) determined the post-main-sequence evolutionary stages for the stars in the Lick planet search sample by comparing their colors and magnitudes with evolutionary models. Since models for stars on the RGB and HB partially overlap in color-magnitude diagrams, they computed a likelihood for each star that it is in either of the two evolutionary phases. Based on their results, 70 stars (19%) in our sample are more likely on the RGB, while 301 (81%) are on the HB. Including the two secure planets presented here, a total of 14 planetary systems have been discovered in the Lick sample. Twelve of the host stars are on the HB, while only two host stars are more likely still ascending the RGB. Defining the planet frequency as the number of planets divided by the number of stars in the parent sample, the planet frequencies and their statistical uncertainties are $4.29^{+4.00}_{-2.32}\%$ and $4.65^{+1.56}_{-1.21}\%$, for the RGB and HB stellar populations, respectively.

The Express survey ([Jones et al. 2011](#)) is the only other giant star survey besides the Lick survey for which evolutionary stages have been published, based on the comparison of the positions of the stars in the HR diagram with evolutionary tracks using the interpolation method. Of the 164 stars of the Express sample, 122 are on the RGB and 42 on the HB, representing 76% and 24% of the overall population, respectively. In order to compare both samples (Lick and Express) in a consistent way, we re-determined the evolutionary stages of the Express stars using the method of [Stock et al. \(2018\)](#). We now find 101 stars (62%) ascending the RGB, while 63 (38%) are on the HB. Just as for the Lick sample, some stars previously thought to be on the RGB are rather on the HB. This might be explained by the bias toward the RGB present in the interpolation method, as discussed by [Stock et al. \(2018\)](#).

We determined the number of planets orbiting host stars from the Express survey by cross-matching their published target list and the NASA Exoplanet Archive. Of the total of 16 planetary systems hosting 18 planets, 11 host stars are on the RGB and five are on the HB, that is, the RGB and HB planet frequencies are $12.87^{+4.24}_{-3.40}\%$ and $7.94^{+5.02}_{-3.39}\%$, respectively.

In each of the two surveys, the planet frequencies for the RGB and HB evolutionary stages are consistent with each other. This indicates that there is no strong effect due to stellar evolution in the planet frequency, as expected from theoretical models ([Villaver et al. 2014](#); [Kunitomo et al. 2011](#)). It is thus justified to compute the planet frequency also for the full samples, irrespective of the stellar evolutionary stage. The planet frequency in the Lick sample is $4.58^{+1.36}_{-1.09}\%$, while the planet frequency in the Express sample is $10.98^{+3.01}_{-2.48}\%$, about twice as large as in the Lick sample.

Obviously, this mismatch could be due to differences in the quality of the available data, or different criteria for publishing. The frequencies reported here refer only to the published planets and should thus be considered only as lower limits. There are indeed several additional possible planets in the Lick sample, but we require more data to confirm them. However, the most probable reason for the smaller planet frequency in the Lick sample is that it contains, on average, more massive stars, which harbor fewer planets ([Reffert et al. 2015](#)). About one third of the Lick stars are more massive than $2.5 M_{\odot}$, while this applies to only 4% of the stars in the Express sample. This could profoundly affect the overall planet frequencies of the samples.

To compare the properties of the planet population in evolved stars to their main-sequence progenitors ([Borgniet et al. 2019](#)),

Fig. 16. Posterior distributions HD 25723 system orbital parameters. Each panel contains $\sim 50\,000$ samples that are tested for 100 kyr dynamical stability using the MVS integrator. Stable samples are plotted in black, while non-stable samples are plotted in red. The *upper panels* show the probability density distribution of each orbital parameter of the stable samples (black) and of the non-stable samples (red). Contours indicate the 68.3%, 95%, and 99.7% confidence interval levels (i.e., 1σ , 2σ , and 3σ). The blue and green cross indicate the dynamical best-fit solution and the stable solution, respectively.

true planet occurrence rates based on a thorough assessment of the detection completeness as well as the selection criteria for the survey targets are needed. For the Lick and Express surveys, these occurrence rates will be published by Wothoff et al. (in prep.).

5. Summary

We report the detection of two substellar companions orbiting the K giant stars, HD 25723 and 17 Sco, based on RV data taken at the Lick Observatory. HD 25723 b has a mass of $2.3 M_J$, and 17 Sco b has a mass of $4.3 M_J$. Both have almost circular orbits,

similarly to the planets found orbiting other K giant stars. The radial velocity variability has been consistent for about 12 yr, and there are no indications in the photometry that point toward reasons for the observed RV variability other than an orbiting companion.

We find evidence of a second companion orbiting HD 25723, however it is not possible to provide a robust claim with the current data. Additional RV data is crucial to confirming the planetary hypothesis.

On the other hand, the periodic RV variations observed for 3 Cnc and 44 UMa can at the moment not be unambiguously attributed to orbiting companions, as the position of these stars

in the PL diagram suggests that they could possibly be affected by oscillatory convective modes (Saio et al. 2015). Furthermore, their stellar parameters, in particular radius, luminosity and surface gravity, are rather similar to those of γ Dra, NGC 4349-127 and Aldebaran, which have recently been shown to not harbor planetary systems (Hatzes et al. 2018; Delgado Mena et al. 2018; Reichert et al. 2019), despite periodic RV curves over timescales of years.

We also determined the planet frequency as a function of the stellar evolutionary stage for two giant star RV surveys, Lick and Express. As in each survey the planet frequencies for HB and RGB host stars are fully consistent with each other, we conclude that there is no evidence of a strong effect of stellar evolution on the number of planets for stellar populations at different evolutionary stages prior to the AGB phase. Overall, the planet frequency in the Lick survey is $4.3^{+1.3}_{-1.1}\%$, while it is $10.4^{+2.9}_{-2.4}\%$, about twice as high, for the Express survey. This is most likely due to the many more massive stars in the Lick sample, which are known to have smaller planet occurrence rates than the less massive evolved stars (Reffert et al. 2015).

Acknowledgements. We kindly thank the staff of Lick Observatory for their excellent support over many years. Saskia Hekker, Simon Albrecht, Christian Schwab, Julian Stürmer, Christoph Bergmann, Dennis Kügler, Kirsten Vincke, Dominika Wylezalek and David Bauer have spent many nights on Mt. Hamilton to collect spectra, for which we are very grateful. Special thanks are due to Geoff Marcy, Paul Butler, and Debra Fischer for permission to use their equipment and software. M.T.P. acknowledges the support of the DAAD Graduate Scholarship Program. S.R. acknowledges the support of the DFG priority program SPP 1992 “Exploring the Diversity of Extrasolar Planets (RE 2694/5-1)”.

References

- Bedding, T. R., Mosser, B., Huber, D., et al. 2011, *Nature*, **471**, 608
- Boisse, I., Moutou, C., Vidal-Madjar, A., et al. 2009, *A&A*, **495**, 959
- Borgniet, S., Lagrange, A. M., Meunier, N., et al. 2019, *A&A*, **621**, A87
- Butler, R. P., Marcy, G. W., Williams, E., et al. 1996, *PASP*, **108**, 500
- Cameron, E. 2011, *PASA*, **28**, 128
- Chabrier, G., Johansen, A., Janson, M., & Rafikov, R. 2014, *Protostars and Planets VI*, 619
- De Ridder, J., Barban, C., Carrier, F., et al. 2006, *A&A*, **448**, 689
- Delgado Mena, E., Lovis, C., Santos, N. C., et al. 2018, *A&A*, **619**, A2
- Döllinger, M. P., Hatzes, A. P., Pasquini, L., et al. 2007, *A&A*, **472**, 649
- Dumusque, X., Boisse, I., & Santos, N. C. 2014, *ApJ*, **796**, 132
- Farr, W. M., Pope, B. J. S., Davies, G. R., et al. 2018, *ApJ*, **865**, L20
- Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, *PASP*, **125**, 306
- Frink, S., Mitchell, D. S., Quirrenbach, A., et al. 2002, *ApJ*, **576**, 478
- Gaia Collaboration 2018, VizieR Online Data Catalog: *I/345*
- Goodman, J., & Weare, J. 2010, *Commun. Appl. Math. Comput. Sci.*, **5**, 65
- Hatzes, A. P. 2002, *Astron. Nachr.*, **323**, 392
- Hatzes, A. P. & Cochran, W. D. 1993, *ApJ*, **413**, 339
- Hatzes, A. P., & Cochran, W. D. 1995, *ApJ*, **452**, 401
- Hatzes, A. P., Cochran, W. D., Endl, M., et al. 2015, *A&A*, **580**, A31
- Hatzes, A. P., Endl, M., Cochran, W. D., et al. 2018, *AJ*, **155**, 120
- Hekker, S., & Meléndez, J. 2007, *A&A*, **475**, 1003
- Hekker, S., Reffert, S., Quirrenbach, A., et al. 2006, *A&A*, **454**, 943
- Johnson, J. A., Fischer, D. A., Marcy, G. W., et al. 2007, *ApJ*, **665**, 785
- Jones, M. I., Jenkins, J. S., Rojo, P., & Melo, C. H. F. 2011, *A&A*, **536**, A71
- Jones, M. I., Jenkins, J. S., Bluhm, P., Rojo, P., & Melo, C. H. F. 2014, *A&A*, **566**, A113
- Jones, M. I., Jenkins, J. S., Rojo, P., Melo, C. H. F., & Bluhm, P. 2015, *A&A*, **573**, A3
- Kjeldsen, H., & Bedding, T. R. 2011, *A&A*, **529**, L8
- Kochanek, C. S., Shappee, B. J., Stanek, K. Z., et al. 2017, *PASP*, **129**, 104502
- Kunitomo, M., Ikoma, M., Sato, B., Katsuta, Y., & Ida, S. 2011, *ApJ*, **737**, 66
- Lee, B.-C., Mkrtichian, D. E., Han, I., Park, M.-G., & Kim, K.-M. 2012, *A&A*, **548**, A118
- Liu, Y.-J., Sato, B., Zhao, G., et al. 2008, *ApJ*, **672**, 553
- Lovis, C., & Mayor, M. 2007, *A&A*, **472**, 657
- Luque, R., Trifonov, T., Reffert, S., et al. 2019, *A&A*, **631**, A136
- Mitchell, D. S., Reffert, S., Trifonov, T., Quirrenbach, A., & Fischer, D. A. 2013, *A&A*, **555**, A87
- Mortier, A., & Collier Cameron, A. 2017, *A&A*, **601**, A110
- Müller, R. G. 2019, Bachelor thesis, University of Heidelberg
- Niedzielski, A., & Wolszczan, A. 2008, *IAU Symp.*, **249**, 43
- Ortiz, M., Reffert, S., Trifonov, T., et al. 2016, *A&A*, **595**, A55
- Perryman, M. A. C., Lindgren, L., Kovalevsky, J., et al. 1997, *A&A*, **323**, L49
- Quirrenbach, A., Trifonov, T., Lee, M. H., & Reffert, S. 2019, *A&A*, **624**, A18
- Reffert, S., Quirrenbach, A., Mitchell, D. S., et al. 2006, *ApJ*, **652**, 661
- Reffert, S., Bergmann, C., Quirrenbach, A., Trifonov, T., & Küntler, A. 2015, *A&A*, **574**, A116
- Reichert, K., Reffert, S., Stock, S., Trifonov, T., & Quirrenbach, A. 2019, *A&A*, **625**, A22
- Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, *J. Astron. Telescopes Instrum. Syst.*, **1**, 014003
- Saio, H., Wood, P. R., Takayama, M., & Ita, Y. 2015, *MNRAS*, **452**, 3863
- Sato, B., Izumiura, H., Toyota, E., et al. 2007, *ApJ*, **661**, 527
- Sato, B., Izumiura, H., Toyota, E., et al. 2008a, *PASJ*, **60**, 539
- Sato, B., Izumiura, H., Toyota, E., et al. 2008b, *ASP Conf. Ser.*, **398**, 67
- Sato, B., Omiya, M., Harakawa, H., et al. 2012, *PASJ*, **64**, 135
- Setiawan, J., Hatzes, A. P., von der Lühe, O., et al. 2003, *A&A*, **398**, L19
- Shappee, B. J., Prieto, J. L., Grupe, D., et al. 2014, *ApJ*, **788**, 48
- Staudt, P. 2020, Bachelor thesis, University of Heidelberg
- Stock, S., Reffert, S., & Quirrenbach, A. 2018, *A&A*, **616**, A33
- Takarada, T., Sato, B., Omiya, M., et al. 2018, *PASJ*, **70**, 59
- Trifonov, T. 2019, *The Exo-Striker: Transit and Radial Velocity Interactive Fitting Tool for Orbital Analysis and N-body Simulations*, Astrophys. Source Code Libr. [record ascl:1906.004]
- Trifonov, T., Reffert, S., Tan, X., Lee, M. H., & Quirrenbach, A. 2014, *A&A*, **568**, A64
- Trifonov, T., Stock, S., Henning, T., et al. 2019, *AJ*, **157**, 93
- van Leeuwen F. 2007, *A&A*, **474**, 653
- Villaver, E., Livio, M., Mustill, A. J., & Siess, L. 2014, *ApJ*, **794**, 3
- Vogt, S. S. 1987, *PASP*, **99**, 1214
- Wittenmyer, R. A., Endl, M., Wang, L., et al. 2011, *ApJ*, **743**, 184
- Wittenmyer, R. A., Butler, R. P., Wang, L., et al. 2016, *MNRAS*, **455**, 1398
- Wood, P. R. 2015, *MNRAS*, **448**, 3829
- Zechmeister, M., & Kürster, M. 2009, *A&A*, **496**, 577

Appendix A: Photometry and $H\alpha$ indices

Fig. A.1. Photometry time-series data. *Left panels:* HIPPARCOS data, and *right panels* ASAS-SN data.

Fig. A.3. $H\alpha$ index time series computed by [Staudt \(2020\)](#).

Fig. A.2. TESS photometry time-series data for HD 25723 and 44 UMa.