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SWEET-Cat update and MOOGme

A new minimization procedure for high quality spectra

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ABSTRACT

Aims.
Methods.
Results.

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1. Introduction

The study of extrasolar planetary systems is an established field of research. To date, over 3200 extrasolar planets have been discovered around solar-type stars[1]. Most of these have been found thanks to the incredible precision achieved in photometric transit and radial velocity. Especially the latest announcement from the *Kepler* space mission with 1284 confirmed exoplanets (Morton et al. 2016). The increasing number of exoplanets allow us to do statistical studies of the newfound worlds by analyzing their internal structure, atmospheric composition, with more.

A key aspect to this progress is the characterization of the planet host stars. For instance, precise and accurate stellar radii are critical if we want to measure precise values of the radius of a transiting planet (see e.g. Torres et al. 2012). The determination of the stellar radius is in turn dependent on the quality of the derived stellar parameters such as the effective temperature.

2. MOOGme

MOOGme (acronym for MOOG made easy) is a web tool for analyzing spectra. MOOGme is written in Python and works as a wrapper around MOOG (Sneden 1973), and ARES (Sousa et al. 2015) for an all-in-one tool. MOOG is a radiative transfer code under the assumption of local thermodynamic equilibrium (LTE). And ARES is a tool to measure equivalent widths (EW) automatically from a spectrum given a line list. MOOGme has four different functions: Measure EWs with ARES, synthetic fitting, EW method, and abundances, all described below. We use the Kurucz spectral grid from Kurucz (1993).

[1] For an updated table we refer to http://www.exoplanet.eu

2.1. EW measurements

EW measurements are important for the EW method and to obtain abundances. This can be done manually using a tool like IRAF, but often when dealing with a large sample of stars this is not a suitable way to deal with the problem. Therefore tools like ARES exists which can measure the EW of spectral lines automatically. To use this mode of MOOGme, ARES has to be installed and be in the PATH. Then MOOGme just need a spectrum (format should be 1D for ARES to read it) and a line list. For the latter, MOOGme is shipped with some line lists ready to use, in the format suitable for MOOGme. The output will be a line list in the format required for MOOG. The output can be used for either the EW method or the abundance method, both described below.

2.2. EW method

This is a standard method for obtaining parameters from stellar spectra. Here measured EWs are used to calculate abundances using a given stellar atmosphere model with a given set of atmospheric parameters, effective temperature ($T_{\rm eff}$), surface gravity ($\log g$), metallicity ([Fe/H], where iron often is used as a proxy), and the micro turbulence ($\xi_{\rm micro}$). By removing correlations between the measured abundances (through the measured EWs) and the excitation potential and reduced EW ($\log(EW/\lambda)$) we can constrain $T_{\rm eff}$ and $\xi_{\rm micro}$. By obtaining ionization balance between Fe I and Fe II, that is the average abundance of all Fe I lines are equal to the average abundance of all Fe II lines, we constrain $\log g$. Last, we change the input [Fe/H] to match that of the average output [Fe/H]. Hence we have four criteria to minimize simultaneously:

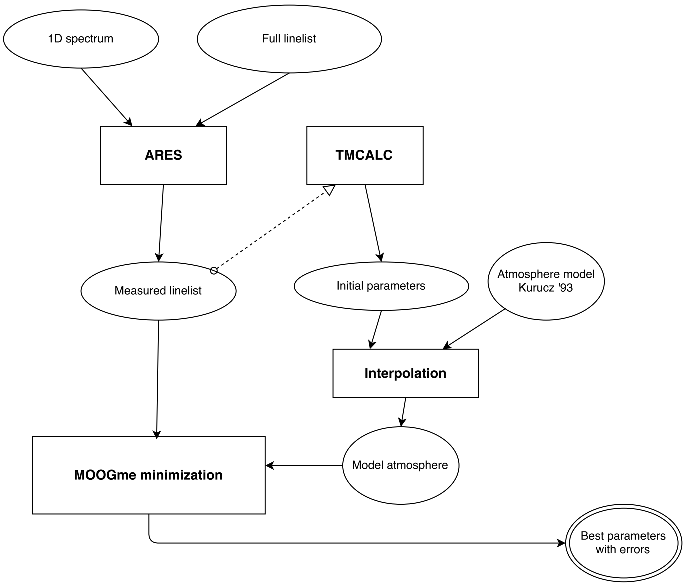

Fig. 1. A general overview over MOOGme from spectrum to parameters.

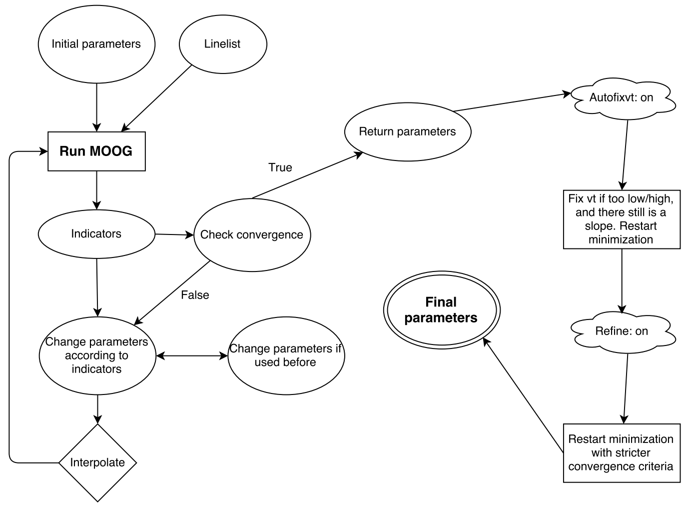

Fig. 2. A schematic overview over the minimization for MOOGme with the EW method.

1. The slope between abundance and excitation potential ($a_{\mathrm{EP}} \leq 0.001$).
2. The slope between abundance and reduced EW ($a_{\mathrm{RW}} \leq 0.003$).
3. The difference between the average abundances of Fe I and Fe II (ΔFe =0.00).
4. Input and output metallicity should be equal.

These criteria we denote as indicators for the physical parameters we are trying to minimize for.

There exists many minimization routines available in Python. Most commonly known are the ones from the SciPy ecosystem[2]. There are some pros and cons with using proprietary minimization routines. Pros are that it is already written, and usually there are good documentation in libraries such as SciPy. Cons in this situation is, that most minimization routines are not able to handle multiple criteria at once. A work around is to combine the criteria into one single criteria by e.g. adding them quadratically and minimize that expression instead. The minimization routines are also not physical in the sense that they are not optimized for the problem. These two cons was incitement for writing a minimization optimized for our problem. Here is how it works.

1. Run MOOG once with a user defined initial parameters (default is solar) and calculate a_{EP}, a_{RW}, and ΔFe .
2. Change the atmospheric parameters (T_{eff}, $\log g$, [Fe/H], ξ_{micro}) according to the size of the indicator. A parameter is only changed if it is not fixed.
   - a_{EP}: Indicator for T_{eff}. If this value is positive, then increase T_{eff}.
   - a_{RW}: Same as above but for ξ_{micro}.
   - ΔFe : Same as above but for $\log g$. Positive ΔFe means $\log g$ should be decreased.
3. For [Fe/H] it is changed to the output [Fe/H] in each iteration (if free).
4. If the new parameters have already been used in a previous, then change them slightly. This is done by drawing a random number from a Gaussian distribution with a mean at the previous value and a sigma equal to the absolute value of the indicator.
5. Calculate a new atmospheric model by interpolating a grid so we have the requested parameters and run MOOG once again.
6. For each iteration save the parameters used and the quadratic sum of the indicators. If we do not reach convergence, then return the best found parameters.

By using the indicators like this, we can relative fast reach convergence. There are some interdependencies among the indicators. E.g. by changing T_{eff} all indicators will be affected, however the effect is strongest for a_{EP}.

2.2.1. Options

It is possible to run the EW method with a set of different options which will be described here.

fixteff Fix T_{eff}. Same is available for $\log g$ (fixlogg), [Fe/H] (fixfeh), and ξ_{micro} (fixvt).

outlier Remove outliers after the first run with the minimization routine and restarting the minimization from the previous best parameters. The options are to remove all outliers above 3σ once or iteratively, or remove one outlier above 3σ once or iteratively.

autofixvt If the minimization routine does not converge and ξ_{micro} is close to 0 or 10 with a significant a_{RW}, then fix ξ_{micro}.

refine After the minimization is done, run it again from the best found parameters but with more strict criteria. If this option is set, it will always be the last step (after removal of outliers and the use of teffrange).

If ξ_{micro} is fixed it is changed at each iteration according to an empirical relation. For dwarfs it follows the one presented in Tsantaki et al. (2013) and for giants it follows the one presented in Adibekyan et al. (2015). We use the line list presented in Sousa et al. (2008) for stars. However, this line list does not work well for cool stars. This was fixed by Tsantaki et al. (2013) removing some lines from Sousa et al. (2008). For stars cooler than 5200 K we rederive the atmospheric parameters after removing lines so the line list resemble that of Tsantaki et al. (2013).

All restarts of the minimization routine is done with initial condition at the last found best parameters.

[2] `http://scipy.org`

2.3. Abundance method

We made a mode to calculate abundances for different elements based on the measured EW. Here we require a line list with the EW of the elements and the corresponding atmospheric parameters for the star of interest. We provide a line list with XXX elements ready to use. The results are saved to a table.

2.4. Testing MOOGme

To test the EW method implemented in MOOGme we derive parameters from the 582 sample by Sousa et al. (2011). We use ARES2 to measure the EWs. ARES can give an estimate on the signal to noise ratio (SNR) by analyzing the continuum in given intervals. For solar type stars the following intervals are working well: 5764-5766 Å, 6047-6053 Å, and 6068-6076 Å. From the estimated SNR, ARES can give an estimate on the very important *rejt* parameters (see Sousa et al. 2015, for more information). After measuring the EWs with ARES, we use the MOOGme minimization described in Section 2.2 to determine the stellar atmospheric parameters. The results are presented in Figure 3 which shows $T_{\rm eff}$, $\log g$, [Fe/H], and $\xi_{\rm micro}$ for MOOGme against those of Sousa et al. (2011).

The sample contains stars with $T_{\rm eff}$ too cold for the line list used. As described in Section 2.2 we should then apply the *tefrange* option to compensate by converting the normal line list by Sousa et al. (2008) to the line list presented in Tsantaki et al. (2013). However, this line list was not available when Sousa et al. (2011) derived parameters, hence we do not apply this option in order to make a better test for MOOGme.

The mean of the difference between parameters from Sousa et al. (2011) and those by MOOGme is presented in Table 1.

Table 1. The difference in derived parameters by Sousa et al. (2011) and MOOGme.

Parameter	Mean difference	Mean difference (same line list
$T_{\rm eff}$	16 ± 36 K	21 ± 11
$\log g$	-0.04 ± 0.07	-0.007 ± 0.009
[Fe/H]	0.03 ± 0.02	0.004 ± 0.009
$\xi_{\rm micro}$	-0.04 ± 0.14 km/s	0.04 ± 0.02 km/s

We see small offsets that can be due to different versions of MOOG, different line lists, and different minimization routine. We therefore randomly selected 20 stars with different $T_{\rm eff}$ and used the line list directly from Sousa et al. (2011) to derive parameters. The results are presented in the last column of Table 1. We note that the $\log gf$ values from the original line lists by Sousa et al. (2011), which used the MOOG 2002 version, were not changed for the 2014 version of MOOG. This might lead to some errors as well. However, the offsets are very small and compatible with the errors on parameters normally obtained from high quality spectra.

2.5. Web interface

We provide a web interface for MOOGme. In the web interface it is possible to use some of the line list provided with MOOGme to measure EWs of a spectrum (has to be provided by the user). This can be used for all the available MOOGme methods described above.

The web interface can be found at the following link `super-cool-address-with-MOOGme`.

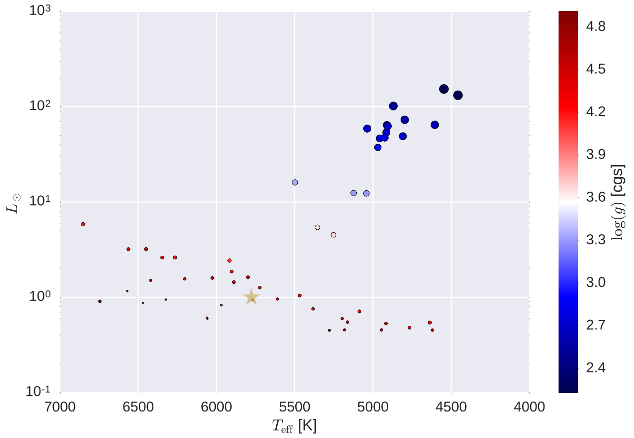

Fig. 4. Hertzprung-Russel diagram of our sample with the Sun as a yellow star. The size of the points represents the $\log g$, with bigger points being smaller $\log g$ (giants), and vice versa. The colour code show the same as the size. Red points are the dwarfs, while blue points are the giants.

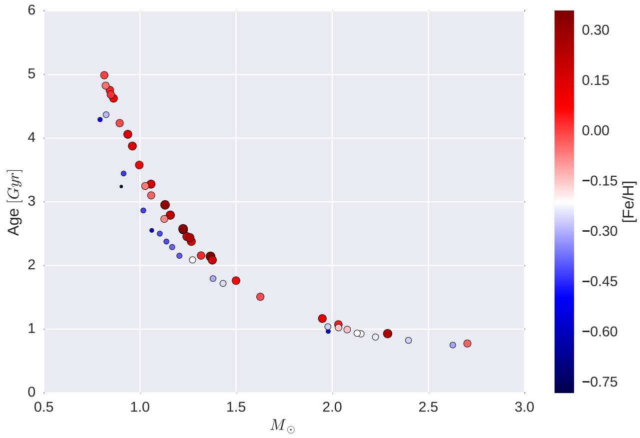

Fig. 5. Age versus mass for our sample, with colours representing the [Fe/H].

3. New spectroscopic parameters for 49 planet hosts

Here we present the sample of 50 stars. We were unable to derive parameters for HD77065. This is a spectroscopic binary according to Pourbaix et al. (2004).

The remaining 49 stars are presented in Table 2.

We present a Hertzprung-Russel diagram (HRD) of our sample in Figure 4.

Figure 4 is made with a tool for post processing the results saved to a table by MOOGme. We also use *isochrones* (Morton 2015) to give an estimate of the age. The mass estimation is based on the relation by Torres et al. (2010). The age estimation is dependent on the mass of the star and the metallicity, which can be seen Figure 5.

4. Conclusion

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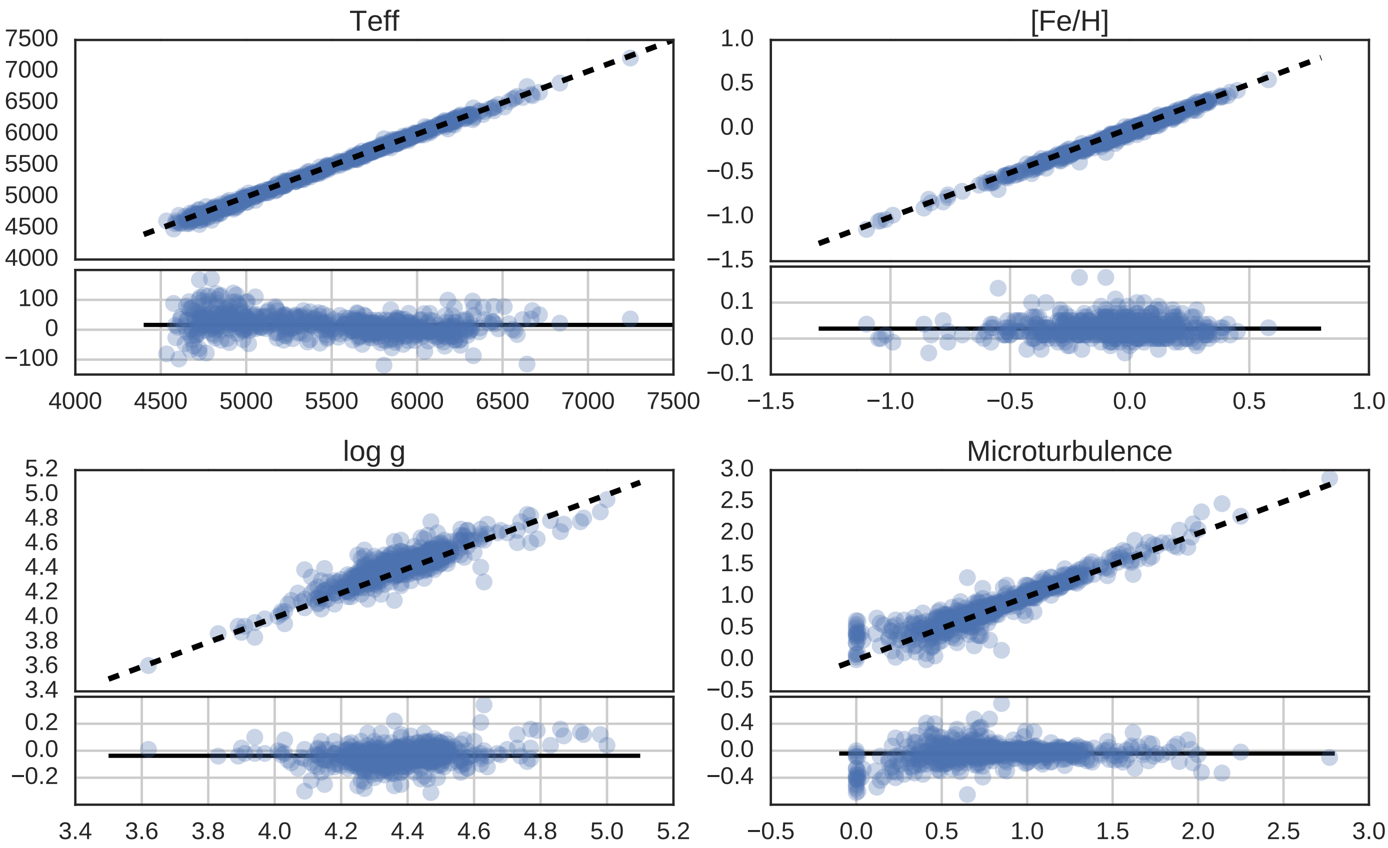

Fig. 3. Stellar atmospheric parameters derived by MOOGme compared to the sample by Sousa et al. (2011).

IF/00028/2014, respectively, and POPH/FSE (EC) by FEDER funding through the program "Programa Operacional de Factores de Competitividade - COMPETE". E.D.M. and B.J.A. acknowledge the support from FCT in form of the fellowship SFRH/BPD/76606/2011 and SFRH/BPD/87776/2012, respectively. This work also benefit from the collaboration of a cooperation project FCT/CAPES - 2014/2015 (FCT Proc 4.4.1.00 CAPES). AM received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement number 313014 (ETAEARTH). This research has made use of the SIMBAD database operated at CDS, Strasbourg (France).

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Table 2. The derived parameters for the 49 stars in our sample.

Star	T_{eff} (K)	$\log g$ (dex)	[Fe/H] (dex)	ξ_{micro} (km/s)	ξ_{micro} fixed?	Program ID
WASP-76	6347 ± 52	4.29 ± 0.08	0.36 ± 0.04	1.73 ± 0.06	no	
WASP-82	6563 ± 55	4.29 ± 0.10	0.18 ± 0.04	1.93 ± 0.08	no	
WASP-88	6450 ± 61	4.24 ± 0.06	0.03 ± 0.04	1.79 ± 0.09	no	
WASP-95	5799 ± 31	4.29 ± 0.05	0.22 ± 0.03	1.18 ± 0.04	no	
WASP-97	5723 ± 52	4.37 ± 0.07	0.31 ± 0.04	1.03 ± 0.08	no	
WASP-99	6324 ± 89	4.70 ± 0.11	0.27 ± 0.06	1.83 ± 0.12	no	
HATS-1	5969 ± 46	4.61 ± 0.06	−0.04 ± 0.04	1.06 ± 0.08	no	
Qatar-2	4637 ± 316	4.23 ± 0.61	0.09 ± 0.17	0.63 ± 0.83	no	
WASP-44	5612 ± 80	4.47 ± 0.30	0.17 ± 0.06	1.32 ± 0.13	no	
HAT-P-46	6421 ± 121	4.53 ± 0.14	0.16 ± 0.09	1.67 ± 0.18	no	
WASP-52	5197 ± 83	4.47 ± 0.30	0.15 ± 0.05	1.16 ± 0.14	no	
WASP-72	6570 ± 85	4.71 ± 0.13	0.15 ± 0.06	2.30 ± 0.15	no	
WASP-75	6203 ± 46	4.42 ± 0.22	0.24 ± 0.03	1.45 ± 0.06	no	
HAT-P-42	5903 ± 66	4.29 ± 0.10	0.34 ± 0.05	1.19 ± 0.08	no	
HATS-5	5383 ± 91	4.40 ± 0.22	0.08 ± 0.06	0.91 ± 0.14	no	
HD 285507	4620 ± 126	4.42 ± 0.61	0.04 ± 0.06	0.74 ± 0.43	no	
HR 228	5042 ± 42	3.30 ± 0.09	0.07 ± 0.03	1.14 ± 0.04	no	
SAND364	4457 ± 104	2.26 ± 0.20	−0.04 ± 0.06	1.60 ± 0.11	no	
GJ 785	5087 ± 48	4.30 ± 0.10	−0.01 ± 0.03	0.69 ± 0.10	no	
HD 120084	4969 ± 40	2.94 ± 0.14	0.12 ± 0.03	1.41 ± 0.04	no	
HD 192263	4946 ± 46	4.43 ± 0.14	−0.05 ± 0.02	0.66 ± 0.12	no	
HIP 107773	4957 ± 49	2.83 ± 0.09	0.04 ± 0.04	1.49 ± 0.05	no	
HD 219134	4767 ± 70	4.32 ± 0.17	−0.00 ± 0.04	0.59 ± 0.24	no	
HD 81688	4906 ± 29	2.69 ± 0.06	−0.21 ± 0.02	1.60 ± 0.03	no	
HD 82886	5124 ± 22	3.30 ± 0.05	−0.25 ± 0.02	1.15 ± 0.03	no	
mu Leo	4605 ± 94	2.61 ± 0.26	0.25 ± 0.06	1.64 ± 0.11	no	
HD 87883	4917 ± 68	4.34 ± 0.19	0.02 ± 0.03	0.46 ± 0.21	no	
HIP 11915	5770 ± 14	4.47 ± 0.03	−0.06 ± 0.01	0.95 ± 0.02	no	
omi UMa	5499 ± 52	3.36 ± 0.07	−0.01 ± 0.05	1.98 ± 0.06	no	
11 Com	4911 ± 38	2.68 ± 0.08	−0.20 ± 0.03	1.56 ± 0.04	no	
HD 102272	5037 ± 80	2.72 ± 0.25	−0.52 ± 0.08	0.67 ± 0.12	no	
HD 104985	4809 ± 48	2.73 ± 0.08	−0.26 ± 0.04	1.65 ± 0.05	no	
HD 114762	6061 ± 83	4.70 ± 0.08	−0.78 ± 0.05	0.02 ± 0.26	no	
omi CrB	4915 ± 33	2.74 ± 0.08	−0.14 ± 0.03	1.57 ± 0.04	no	
HD 152581	5355 ± 82	3.65 ± 0.18	−0.39 ± 0.07	0.60 ± 0.15	no	
HD 155358	5917 ± 51	4.12 ± 0.08	−0.55 ± 0.04	1.06 ± 0.08	no	
42 Dra	4547 ± 55	2.23 ± 0.10	−0.31 ± 0.03	1.54 ± 0.05	no	
HD 220842	6027 ± 30	4.35 ± 0.05	−0.08 ± 0.03	1.19 ± 0.04	no	
14 And	4797 ± 44	2.58 ± 0.11	−0.23 ± 0.03	1.58 ± 0.04	no	
HD 233604	4925 ± 44	2.79 ± 0.11	−0.15 ± 0.03	1.62 ± 0.05	no	
HD 37124	5468 ± 32	4.28 ± 0.04	−0.43 ± 0.03	0.67 ± 0.07	no	
HD 97658	5182 ± 43	4.50 ± 0.12	−0.29 ± 0.03	0.77 ± 0.11	no	
Kepler-444	5163 ± 40	4.41 ± 0.11	−0.50 ± 0.03	0.78 ± 0.10	no	
WASP-100	6853 ± 209	4.15 ± 0.26	−0.30 ± 0.12	1.87 ± 0.02	yes	
HAT-P-24	6470 ± 181	4.75 ± 0.26	−0.41 ± 0.10	1.40 ± 0.03	yes	
HAT-P-39	6745 ± 236	4.91 ± 0.46	−0.21 ± 0.12	1.53 ± 0.04	yes	
WASP-61	6265 ± 168	4.21 ± 0.21	−0.38 ± 0.11	1.44 ± 0.02	yes	
HD 70573	5889 ± 186	4.32 ± 0.27	−0.42 ± 0.13	1.14 ± 0.01	yes	