

# SWEET-Cat update and MOOGme

## A new minimization procedure for high quality spectra

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### ABSTRACT

*Aims.*

*Methods.*

*Results.*

**Key words.** data reduction: high resolution spectra – stars individual: Arcturus – stars individual: HD010853

## 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<sup>1</sup>. 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 new tool for analyzing spectra. MOOGme is written in Python and works as a wrapper around MOOG (Snedden 1973), and ARES (Sousa et al. 2015a) 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.

### 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.

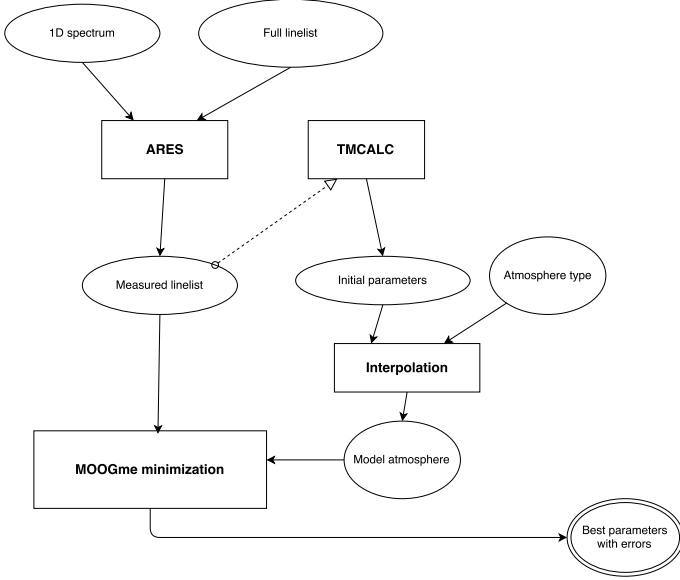
### 2.2. Synthetic fitting

FOR MARIA :)

### 2.3. EW method

This is the second 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 ( $T_{\text{eff}}$ ), surface gravity ( $\log g$ ), metallicity ( $[\text{Fe}/\text{H}]$ , where iron often is used as a proxy), and the micro turbulence ( $\xi_{\text{micro}}$ ). By removing correlations between the measured abundances (through the measured EWs) and the excitation potential and reduced EW ( $\log(EW/\lambda)$ ) we can constrain  $T_{\text{eff}}$  and  $\xi_{\text{micro}}$ . By obtaining ionization balance between Fe I and Fe II, that is the average abun-

<sup>1</sup> For an updated table we refer to <http://www.exoplanet.eu>



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

dance 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  $[\text{Fe}/\text{H}]$  to match that of the average output  $[\text{Fe}/\text{H}]$ . Hence we have four criteria to minimize simultaneously:

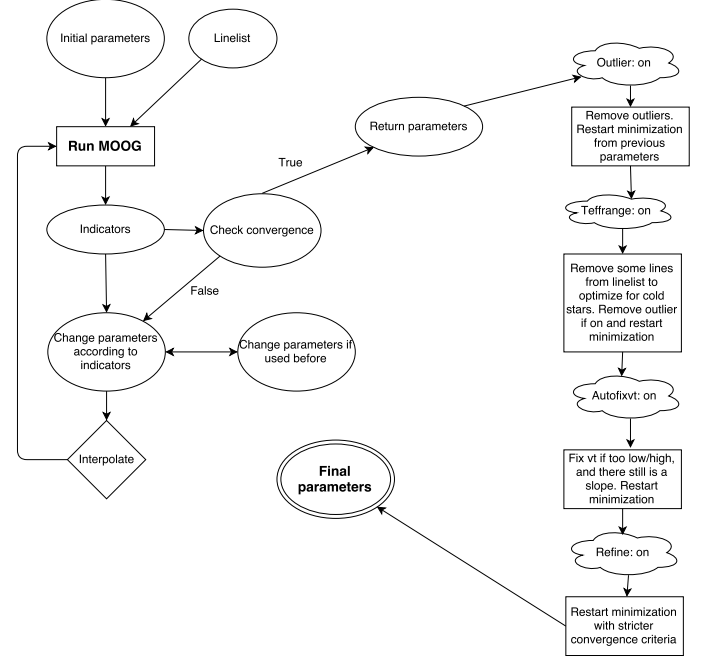
1. The slope between abundance and excitation potential ( $a_{\text{EP}}$ ).
2. The slope between abundance and reduced EW ( $a_{\text{RW}}$ ).
3. The difference between the average abundances of Fe I and Fe II ( $\Delta\text{Fe}$ ).
4. Input and output metallicity.

Which we together denote as indicators.

There exists many minimization routines available in Python. Most commonly known are the ones from the SciPy ecosystem<sup>2</sup>. 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  $a_{\text{EP}}$ ,  $a_{\text{RW}}$ , and  $\Delta\text{Fe}$ .
2. Change the atmospheric parameters ( $T_{\text{eff}}$ ,  $\log g$ ,  $[\text{Fe}/\text{H}]$ ,  $\xi_{\text{micro}}$ ) according to the size of the indicator. A parameter is only changed if it is not fixed.
  - $a_{\text{EP}}$ : Indicator for  $T_{\text{eff}}$ . If this value is positive, then increase  $T_{\text{eff}}$ .
  - $a_{\text{RW}}$ : Same as above but for  $\xi_{\text{micro}}$ .
  - $\Delta\text{Fe}$ : Same as above but for  $\log g$ . Positive  $\Delta\text{Fe}$  means  $\log g$  should be decreased.
3. For  $[\text{Fe}/\text{H}]$  it is changed to the output  $[\text{Fe}/\text{H}]$  in each iteration (if free).

<sup>2</sup> <http://scipy.org>



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

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  $T_{\text{eff}}$  all indicators will be affected, however the effect is strongest for  $a_{\text{EP}}$ .

### 2.3.1. Options

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

- model**: Change which type of model atmosphere to use. Currently the following are available: Kurucz 95, Marcs, and Kurucz from APOGEE.
- weights**: Calculate the slopes with an weight based on the distance from the mean.
- fixteff**: Fix  $T_{\text{eff}}$ . Same is available for  $\log g$  (fixlogg),  $[\text{Fe}/\text{H}]$  (fixfeh), and  $\xi_{\text{micro}}$  (fixvt).
- iterations**: The maximum number of iterations (160 by default).
- EPcrit**: The criteria for  $a_{\text{EP}}$  to reach convergence (0.001 by default).
- RWcrit**: The criteria for  $a_{\text{RW}}$  to reach convergence (0.003 by default).
- ABdiffcrit**: The criteria for  $\Delta\text{Fe}$  to reach convergence (0.01 by default).
- MOOGv**: The version of MOOG being used (2014 by default).
- 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  $3\sigma$  once or iteratively, or remove one outlier above  $3\sigma$  once or iteratively.

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

**teffrange** This is a special option for two of the line list shipped with MOOGme. The ones from Sousa et al. (2015b) and Tsantaki et al. (2013). The latter is a subset of the former optimized for cooler stars. If this option is set, and the former line list is used for a cool star ( $T_{\text{eff}}$  found after the minimization), then remove the lines from the used line list to match the latter line list and rerun the minimization routine.

**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  $\xi_{\text{micro}}$  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).

#### 2.4. 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.

### 3. Testing MOOGme

To adequate test the EW method implemented in MOOGme we derive parameters from the sample by Sousa et al. (2008). 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. 2015a, for more information). After measuring the EWs with ARES, we use the MOOGme minimization described in Section 2.3 to determine the stellar atmospheric parameters. The results are presented in Figure 3 which shows  $T_{\text{eff}}$ ,  $\log g$ ,  $[\text{Fe}/\text{H}]$ , and  $\xi_{\text{micro}}$  for MOOGme against those of Sousa et al. (2008).

### 4. 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 1.

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

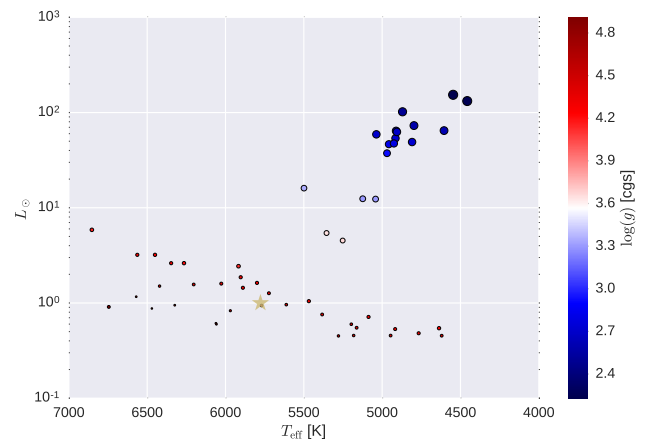
Figure 4 is made with a tool for post processing the results saved to a table by MOOGme. We also use *isochrones* (Morton 2015) to give an estimate of the age. The mass estimation is based on the relation by Torres et al. (2010). The age estimation is dependent on the mass of the star and the metallicity,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

### 5. Conclusion

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**Fig. 3.** Stellar atmospheric parameters derived by MOOGme compared to the sample by Sousa et al. (2008).



**Fig. 4.** Hertzsprung-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.

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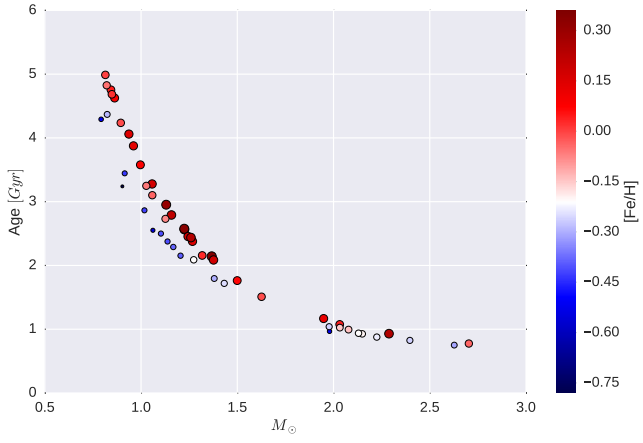
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**Table 1.** The derived parameters for the 65 stars in our sample.

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

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## Appendix A: An appendix



**Fig. 5.** Age versus mass for our sample, with colours representing the  $[\text{Fe}/\text{H}]$ .