Determination of stellar parameters for FGK-dwarf stars: the NIR approach

by

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A thesis submitted in conformity with the requirements
for the degree of Doctor of Philosophy
Graduate Department of Departamento de Fisica e Astronomia
University of Porto

Dedication

To Linnea, Henriette, and Rico
For always supporting me

Acknowledgements

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Abstract

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Resumo

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Chapter 1

Introduction

Ever since the dawn of time, the humankind have looked at the stars and wondered if we are alone in this Universe. To answer this question, one must look toward the field of extrasolar planets (exoplanets). This is a rapidly growing field in astronomy and science in general. Since the first confirmed discovery of an exoplanet around a millisecond pulsar in 1992 by Wolszczan and Frail (1992) and three years later, the more interesting exoplanet 51 Peg b discovered around a solar-type star by Mayor and Queloz (1995), more than 3600 exoplanets have been discovered at the time of writing, July 2017[1].

With the discoveries of exoplanets, the main focus is now mainly on finding the twin of Earth, that is a planet that can harbour life as we know it. However, it is not enough to simply discover small rocky exoplanets. Accurate and precise determination of the stellar parameters are crucial as the planetary parameters (radius, mass, bulk density, etc.) are directly derived from their host's parameters.

In this chapter there will be a general introduction to exoplanets, detection methods, and characterisation (Section 1.1). Then a throughout introduction on the exoplanet host stars (Section 1.2), which is the main focus on this thesis. While learning about host stars, and stars in general, the results have wide-spread applications, where some will briefly be discussed in the end of this chapter (Section 1.3) before an introduction on what this thesis will consists of (Section 1.4).

1.1 Exoplanets

The holy grail in the field of exoplanets is to find the first exoplanet with life. This is by no means an easy task. To give an idea of the difficulty of detecting life on an exoplanet, one must understand all the difficulties to simply detect and confirm an exoplanet. This will shortly be described in the sections below

1.1.1 Detecting exoplanets

There are sex ways of detecting exoplanets, some with advantages over others. In combination with each other, one can potentially learn a lot about the exoplanet(s).

It is important to note, that different things might mimic planetary signals, however they will not be described in this thesis. The confirmation of an exoplanet often happen, when two techniques are able to detect the same exoplanet.

[1] http://exoplanet.eu/

1.1.1.1 Transit method

The most successful method, if based on numbers of exoplanets detected, is the transit method. This is a well-known method in astronomy, however only used in the last decade for detecting exoplanets. Before this, it has been used extensively for finding and characterising binary stars. The difference here is, that the exoplanet does not radiate (or at least very little radiation). An example of an exoplanet transiting a star can be seen in Figure 1.1.

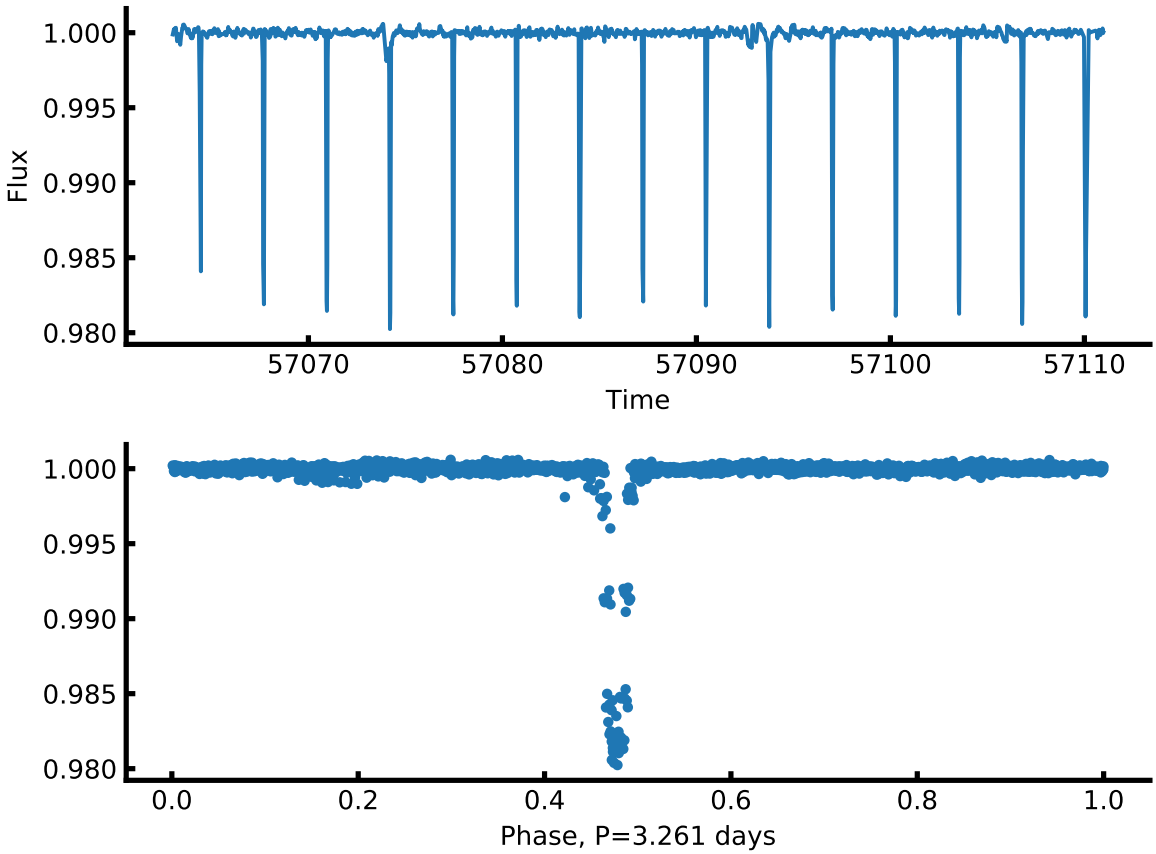

Figure 1.1: *Upper plot*: The lightcurve of a star with an exoplanet transiting. *Lower plot*: The phase curve of the above lightcurve.

As an exoplanet orbit a star, it might transit its host as seen from an observer here on Earth. This signal might be detected if the star's brightness is being monitored as a periodic signal. The decrease in brightness as the planet transit the star is directly related to ration between the stellar radius R_* and the planetary radius R_p:

$$k = \sqrt{\frac{R_p}{R_*}}, \tag{1.1}$$

where k is the depth of the transit compared to the total stellar brightness.

It is possible to obtain the radius of an exoplanet with this method. However, detailed analysis of the phase curve of an exoplanet can reveal the surface temperature of the exoplanet. The transit described

above is also known as the primary transit. If it is possible to detect the secondary transit, that is when the exoplanet goes behind the star as seen from Earth, the difference in light (planet + star right before secondary transit compared to just star) gives the flux of the planet and thus the surface temperature. This is a difficult task as secondary transits are intrinsic faint.

1.1.1.2 Radial velocity method

The radial velocity method is the indirect study of the motion of the host star using the Doppler effect caused by an orbiting exoplanet. This together with the transit method described above is by far the most successful methods to detect and characterise exoplanets. The periodic signal created by the exoplanet on the host star depends on the mass ratio between the star M_* and the planet M_p:

$$K = \frac{28.4329\,\mathrm{km/s}}{\sqrt{1-e^2}} \frac{M_p \sin i}{M_{\mathrm{Jup}}} \left(\frac{M_* + M_p}{M_\odot}\right)^{-2/3} \left(\frac{P}{1\,\mathrm{year}}\right) \tag{1.2}$$

where K is the semi-amplitude of the sinusoidal, e is the eccentricity, i is the inclination, P is the orbital period, and M_{Jup} is the mass of Jupiter. Since $M_* \gg M_p$, the term $M_* + M_p \simeq M_*$ in order to simplify the equation. Often a circular orbit is assumed, $e = 0$. The sinusoidal motion of the star can be seen in Figure 1.2 where both the time series and the phase curve is presented for an exoplanet.

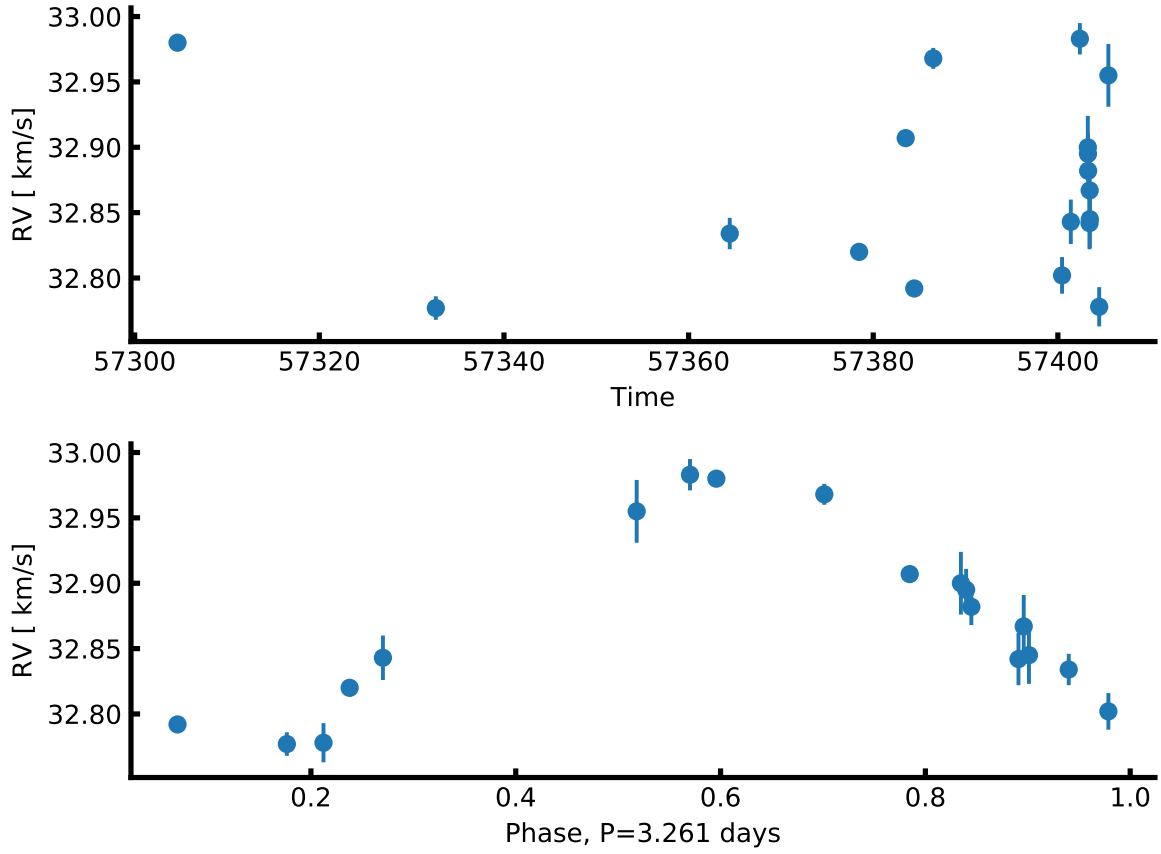

Figure 1.2: *Upper panel*: RV time series of EPIC 9792 from the SOPHIE spectrograph. *Lower panel*: Phase curve of the time series above, using the period of 3.261 days.

In order to apply the radial velocity method for detecting exoplanets, it is necessary to collect spectra, high resolution but often not high S/N, in order to cover most part of the phase of the orbit. These spectra are often combined after the detection of the exoplanet, in order to increase the S/N. This combined spectrum can then be used for characterising the host star.

This method is sensitive to close-in massive exoplanets, also known as hot Jupiters. In combination with the above mentioned transit method, the mass and radius of an exoplanet can be derived, and thus the bulk density which might give hints of the structure and composition of the exoplanet.

1.1.1.3 Direct imaging

Direct imaging is probably the easiest method to understand, however it is quite difficult to actually use this technique. In its core, one has to carefully block the light of a star, and directly imaging the exoplanets around it. However, it is extremely difficult to block the light of the host star and find the reflected light of the exoplanet(s) in orbit.

This technique is sensitive to exoplanets which reflect a lot of light, i.e. a high albedo, and in wide orbits as they are less contaminated by the residual starlight.

1.1.1.4 Astrometry

Using astrometry to detect exoplanets is very similar to the RV method described above in Section 1.1.1.2. Here an observer carefully detect the minute motion of a star caused by an exoplanet. Unlike the RV method, this technique (astrometry) actually looks for changes in the coordinates of the star. This technique has also been used to detect low luminosity stellar companions as e.g. Sirius B.

This technique is sensitive to massive exoplanets as they cause a larger motion compared to lighter companions.

1.1.1.5 Transit timing variation

This technique of detecting exoplanets is a highly indirect method of detecting exoplanets. Here an observer first detect a transiting exoplanet as explained in Section 1.1.1.1. Then variations in the occurrence of mid-transit can be detected if a second non-transiting exoplanet interact with the primary transiting exoplanet (planet-planet interaction). This interaction will periodically course the mid-transit to happen ahead/behind of the time if only one exoplanet would be present.

A careful analysis of the transit timing variations (TTV) can lead to the mass of the secondary non-transiting exoplanet. However, its radius will be unknown. Most of these exoplanets pairs which shows TTV are in an orbital resonant. This technique as well, is more sensitive to massive exoplanets as they will induce a higher signal.

1.1.1.6 Microlensing

This technique is very exotic and not very useful, however since a few exoplanets have been discovered by this technique it deserves a mentioning. The core theory in this technique is the well-known General Relativity. Here an observer looks at a distant star (star A) as a star between the observer and the distant star (star B) passes in front of the line of sight. Star B will act as a microlens and increase the magnitude of star A. This increase of magnitude will reach its maximum as the two stars are most aligned as seen from Earth.

To use this for detecting exoplanet, there will have to be an exoplanet orbiting star B. This act like another lens, momentarily make a secondary increase in magnitude. The amount of increase in magnitude is related to the mass of the exoplanet. The higher the mass, the higher the effect.

While this exotic technique is interesting and has proven successful, it is not very useful as it only occurs once. The stars observed with this technique are often faint, thus making follow-up RV detection very difficult if not impossible with the current instruments.

1.1.2 Towards the Earth twin

The above mentioned techniques will be used to find the Earth twin. Especially will the two first techniques (transit and RV method) be the ones finding the smallest exoplanets as a wide range of instruments are being developed dedicated for this. Since the detection of the first exoplanet around a solar-type star by Mayor and Queloz (1995), the community has been able to detect lower mass exoplanets as seen in Figure 1.3.

Write about JWST, Espresso, NIRPS, etc.

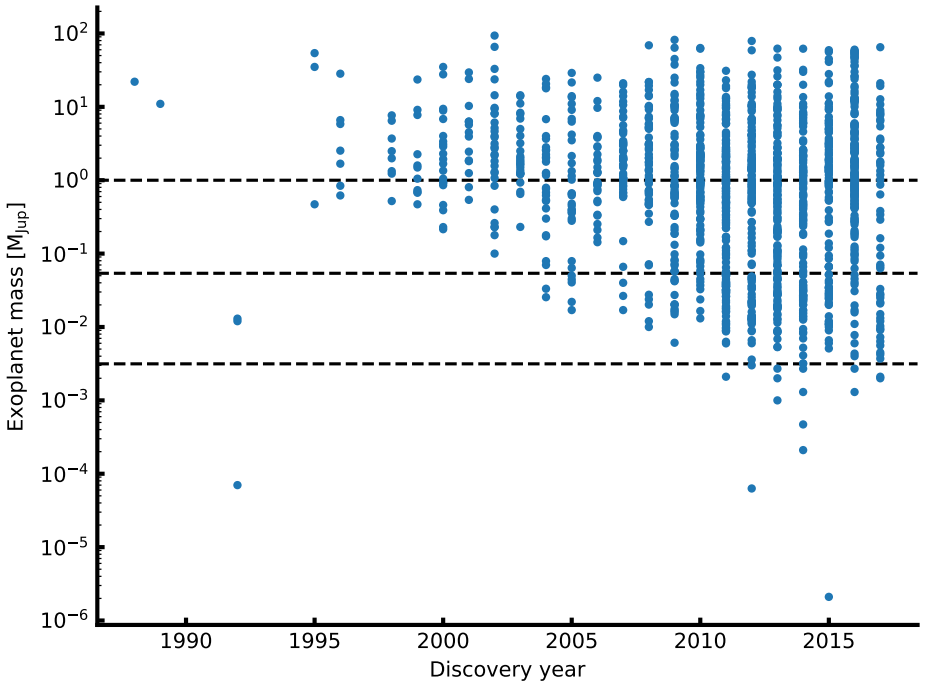

Figure 1.3: The mass of exoplanet since the detection of the first exoplanet until now. The horizontal lines are the mass of Jupiter (upper), Neptune (middle), and Earth (lower).

While the first many discoveries of exoplanets were the, at the time, exotic and strange hot Jupiter like exoplanets in close orbits, the time have come to detect exoplanets with both lower mass and wider orbits. It is crucial to have high precision instruments and long surveys to detect those exoplanets. Missions as *Kepler* and CoRoT have been excellent for this, since they have focused on few fields of the sky for a long time.

The first place to look for Earth's twin is around a solar twin. However, since these stars are quite hot, the habitable zone will also be far from the host star. Indeed, to detect a copy of our own solar system we would need to detect the minute signature of an exoplanet in a 1 year orbit around its host

star (a solar twin). If detected with the transit method, more than one transit is needed, hence this will take at least two years, and probably even longer. The endeavour to get the follow-up RV afterwards will also be extremely challenging with today's technology, and only the next generation of spectrographs will be able to detect these signals.

Therefore, it is not a surprise that an effort have been towards detecting Earth-like planets around less massive stars. These stars (M stars) are also colder, hence the habitable zone will be closer to its host compared to the more massive and hotter stars. The nature have been kind, since it seems that the M stars are prone to produce rocky planets rather than giant planets. The shorter period means that the surveys can be shorter for these planets. Moreover, since they are smaller the signal from a transit will be easier to detect (see Equation 1.1). Similarly will the RV signal be larger for an Earth-like planet in the habitable zone around an M star compared to a similar exoplanet around a G star. Both due to the lower period and due to the lower mass of the host star (see Equation 1.2).

The ref. is in the proposals

While M stars seems to be the place to look for the Earth's twin, there are still some challenges to tackle. Foremost is the detailed characterisation of the host star, which are particular troublesome for these stars. This is something that will be focused on in the following section.

1.2 Planet host stars

With the present diversity of exoplanets it becomes increasingly important to get an accurate and precise characterisation of the exoplanets in order to study them in samples and on an individual level. An accurate and precise characterisation can give us an idea whether the planet is rocky, composed of water or gaseous.

1.3 Applications from knowing the stars

1.4 This thesis

Appendix A

SWEET-Cat update of 50 planet hosts

Table A.1: Derived parameters for the 50 stars in our sample. The S/N was measured by ARES.

Star	$T_{\rm eff}$ [K]	$\log g$ [cgs]	[Fe /H]	$\xi_{\rm micro}$ [km/s]	$\xi_{\rm micro}$ fixed?	Instrument	S/N
BD -11 4672	4553 ± 75	4.87 ± 0.51	-0.30 ± 0.02	0.14 ± 0.07	yes	FIES	487
BD +49 828	5015 ± 36	2.87 ± 0.09[a]	-0.01 ± 0.03	1.48 ± 0.04	no	FIES	567
GJ 785	5087 ± 48	4.42 ± 0.10	-0.01 ± 0.03	0.69 ± 0.10	no	HARPS	801
HATS-1	5969 ± 46	4.39 ± 0.06	-0.04 ± 0.04	1.06 ± 0.08	no	UVES	155
HATS-5	5383 ± 91	4.41 ± 0.22	0.08 ± 0.06	0.91 ± 0.14	no	UVES	158
HAT-P-12	4642 ± 106	4.53 ± 0.27	-0.26 ± 0.06	0.28 ± 0.63	no	FIES	185
HAT-P-24	6470 ± 181	4.33 ± 0.27	-0.41 ± 0.10	1.40 ± 0.03	yes	UVES	158
HAT-P-39	6745 ± 236	4.39 ± 0.47	-0.21 ± 0.12	1.53 ± 0.04	yes	UVES	127
HAT-P-42	5903 ± 66	4.29 ± 0.10[a]	0.34 ± 0.05	1.19 ± 0.08	no	UVES	130
HAT-P-46	6421 ± 121	4.53 ± 0.14[a]	0.16 ± 0.09	1.67 ± 0.18	no	UVES	208
HD 120084	4969 ± 40	2.94 ± 0.14[a]	0.12 ± 0.03	1.41 ± 0.04	no	ESPaDOnS	852
HD 192263	4946 ± 46	4.61 ± 0.14	-0.05 ± 0.02	0.66 ± 0.12	no	HARPS	415
HD 219134	4767 ± 70	4.57 ± 0.17	0.00 ± 0.04	0.59 ± 0.24	no	ESPaDOnS	725
HD 220842	5999 ± 39	4.30 ± 0.06[a]	-0.08 ± 0.03	1.21 ± 0.05	no	FIES	459
HD 233604	4954 ± 46	2.86 ± 0.11[a]	-0.14 ± 0.04	1.61 ± 0.05	no	FIES	314
HD 283668	4841 ± 73	4.51 ± 0.18	-0.74 ± 0.04	0.16 ± 0.61	no	FIES	592
HD 285507	4620 ± 126	4.72 ± 0.61	0.04 ± 0.06	0.74 ± 0.43	no	UVES	239
HD 5583	4986 ± 35	2.87 ± 0.09[a]	-0.35 ± 0.03	1.62 ± 0.04	no	FIES	933
HD 81688	4903 ± 21	2.70 ± 0.05[a]	-0.21 ± 0.02	1.54 ± 0.02	no	[b]	1350, 860
HD 82886	5123 ± 18	3.30 ± 0.04[a]	-0.25 ± 0.01	1.16 ± 0.02	no	[c]	1198,1294
HD 87883	4917 ± 68	4.53 ± 0.19	0.02 ± 0.03	0.46 ± 0.21	no	ESPaDOnS	753
HIP 107773	4957 ± 49	2.83 ± 0.09[a]	0.04 ± 0.04	1.49 ± 0.05	no	UVES	218
HIP 11915	5770 ± 14	4.33 ± 0.03	-0.06 ± 0.01	0.95 ± 0.02	no	HARPS	709
HIP 116454	5042 ± 72	4.69 ± 0.15	-0.16 ± 0.03	0.71 ± 0.17	no	UVES	412

Table A.1: continued.

Star	$T_{\rm eff}$ [K]	$\log g$ [cgs]	[Fe /H]	$\xi_{\rm micro}$ [km/s]	$\xi_{\rm micro}$ fixed?	Instrument	S/N
HR 228	5042 ± 42	3.30 ± 0.09[a]	0.07 ± 0.03	1.14 ± 0.04	no	UVES	400
KELT-6	6246 ± 88	4.22 ± 0.09[a]	-0.22 ± 0.06	1.66 ± 0.13	no	FIES	374
Kepler-37	5378 ± 53	4.47 ± 0.12	-0.23 ± 0.04	0.58 ± 0.13	no	FIES	205
Kepler-444	5111 ± 43	4.50 ± 0.13	-0.51 ± 0.03	0.37 ± 0.15	no	FIES	675
mu Leo	4605 ± 94	2.61 ± 0.26[a]	0.25 ± 0.06	1.64 ± 0.11	no	ESPaDOnS	354
ome Ser	4928 ± 35	2.69 ± 0.06[a]	-0.11 ± 0.03	1.55 ± 0.04	no	FIES	1168
omi UMa	5499 ± 52	3.36 ± 0.07[a]	-0.01 ± 0.05	1.98 ± 0.06	no	ESPaDOnS	527
Qatar-2	4637 ± 316	4.53 ± 0.62	0.09 ± 0.17	0.63 ± 0.83	no	UVES	97
SAND364	4457 ± 104	2.26 ± 0.20[a]	-0.04 ± 0.06	1.60 ± 0.11	no	UVES	220
TYC+1422-614-1	4908 ± 41	2.90 ± 0.12[a]	-0.07 ± 0.03	1.57 ± 0.05	no	FIES	506
WASP-37	5917 ± 72	4.25 ± 0.15	-0.23 ± 0.05	0.59 ± 0.13	no	FIES	232
WASP-44	5612 ± 80	4.39 ± 0.30	0.17 ± 0.06	1.32 ± 0.13	no	UVES	125
WASP-52	5197 ± 83	4.55 ± 0.30	0.15 ± 0.05	1.16 ± 0.14	no	UVES	125
WASP-58	6039 ± 55	4.23 ± 0.10	-0.09 ± 0.04	1.12 ± 0.08	no	FIES	310
WASP-61	6265 ± 168	4.21 ± 0.21[a]	-0.38 ± 0.11	1.44 ± 0.02	yes	UVES	163
WASP-72	6570 ± 85	4.25 ± 0.13	0.15 ± 0.06	2.30 ± 0.15	no	UVES	174
WASP-73	6203 ± 32	4.16 ± 0.06[a]	0.20 ± 0.02	1.66 ± 0.04	np	[d]	193,231
WASP-75	6203 ± 46	4.42 ± 0.22[a]	0.24 ± 0.03	1.45 ± 0.06	no	UVES	189
WASP-76	6347 ± 52	4.29 ± 0.08[a]	0.36 ± 0.04	1.73 ± 0.06	no	UVES	165
WASP-82	6563 ± 55	4.29 ± 0.10[a]	0.18 ± 0.04	1.93 ± 0.08	no	UVES	239
WASP-88	6450 ± 61	4.24 ± 0.06[a]	0.03 ± 0.04	1.79 ± 0.09	no	UVES	174
WASP-94 A	6259 ± 34	4.34 ± 0.07[a]	0.35 ± 0.03	1.50 ± 0.04	no	UVES	356
WASP-94 B	6137 ± 21	4.42 ± 0.05[a]	0.33 ± 0.02	1.29 ± 0.03	no	UVES	397
WASP-95	5799 ± 31	4.29 ± 0.05[a]	0.22 ± 0.03	1.18 ± 0.04	no	UVES	247
WASP-97	5723 ± 52	4.24 ± 0.07	0.31 ± 0.04	1.03 ± 0.08	no	UVES	219

Table A.1: continued.

Star	$T_{\rm eff}$ [K]	$\log g$ [cgs]	[Fe /H]	$\xi_{\rm micro}$ [km/s]	$\xi_{\rm micro}$ fixed?	Instrument	S/N
WASP-99	6324 ± 89	4.34 ± 0.12	0.27 ± 0.06	1.83 ± 0.12	no	UVES	249
WASP-100	6853 ± 209	4.15 ± 0.26[a]	-0.30 ± 0.12	1.87 ± 0.02	yes	UVES	166

[a] Spectroscopic $\log g$.

[b] Weighted average of ESPaDoNS and FIES results. The parameters are (FIES in parantheses): $T_{\rm eff} = 4870(4934) \pm 30(29)$, $\log g = 2.50(2.73) \pm 0.14(0.05)$, [Fe /H] $= -0.26(-0.19) \pm 0.03(0.02)$, and $\xi_{\rm micro} = 1.50(1.59) \pm 0.03(0.03)$.

[c] Weighted average of ESPaDoNS and FIES results. The parameters are (FIES in parantheses): $T_{\rm eff} = 5124(5121) \pm 22(29)$, $\log g = 3.30(3.31) \pm 0.05(0.07)$, [Fe /H] $= -0.25(-0.24) \pm 0.02(0.02)$, and $\xi_{\rm micro} = 1.15(1.17) \pm 0.03(0.04)$.

[d] Weighted average of UVES and FEROS results. The parameters are (FEROS in parantheses): $T_{\rm eff} = 6313(6162) \pm 61(37)$, $\log g = 4.26(4.14) \pm 0.15(0.06)$, [Fe /H] $= 0.22(0.19) \pm 0.04(0.03)$, and $\xi_{\rm micro} = 1.85(1.61) \pm 0.08(0.04)$.

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