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A homogeneous spectroscopic analysis of host stars of transiting planets[*],[**],[***]

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ABSTRACT

Context. The analysis of transiting extra-solar planets provides an enormous amount of information about the formation and evolution of planetary systems. A precise knowledge of the host stars is necessary to derive the planetary properties accurately. The properties of the host stars, especially their chemical composition, are also of interest in their own right.
Aims. Information about planet formation is inferred by, among others, correlations between different parameters such as the orbital period and the metallicity of the host stars. The stellar properties studied should be derived as homogeneously as possible. The present work provides new, uniformly derived parameters for 13 host stars of transiting planets.
Methods. Effective temperature, surface gravity, microturbulence parameter, and iron abundance were derived from spectra of both high signal-to-noise ratio and high resolution by assuming iron excitation and ionization equilibria.
Results. For some stars, the new parameters differ from previous determinations, which is indicative of changes in the planetary radii. A systematic offset in the abundance scale with respect to previous assessments is found for the TrES and HAT objects. Our abundance measurements are remarkably robust in terms of the uncertainties in surface gravities. The iron abundances measured in the present work are supplemented by all previous determinations using the same analysis technique. The distribution of iron abundance then agrees well with the known metal-rich distribution of planet host stars. To facilitate future studies, the spectroscopic results of the current work are supplemented by the findings for other host stars of transiting planets, for a total dataset of 50 objects.

Key words. stars: fundamental parameters – planetary systems – stars: abundances – stars: statistics

1. Introduction

Almost 60 transiting extra-solar planets have so far been found[1]. This number is small compared to those detections by the radial-velocity technique alone, but the amount of information provided by transiting systems is significantly higher, for the orbits and the structure of the planets. When deriving the planetary properties, a good knowledge of the parent star is important. A sufficiently accurate spectroscopic derivation of effective temperature, surface gravity, and abundances should be based on spectra of both high resolution and high signal-to-noise ratio.

The knowledge of the chemical abundance of the stars harbouring transiting planets paves the way to interesting studies. Santos et al. (2006b) confirmed that they follow the trend of excess metallicity of stars with planets (Gonzalez et al. 2001; Santos et al. 2004; Fischer & Valenti 2005; Sozzetti et al. 2009b). Heavy elements seem to be important to the formation of close-in planets, as indicated by comparing the planetary heavy-metal content with the metallicity of the host star (Guillot et al. 2006). This work will benefit strongly from more accurate and uniform parameters of host stars of transiting planets.

Stellar parameters and chemical abundances have already been derived for most parent stars of transiting planets, usually in a very uniform way within each transit search program, e.g., as in the case of the HAT objects (Bakos et al. 2007b,a; Kovács et al. 2007; Noyes et al. 2008; Pál et al. 2008) and the TrES stars (Sozzetti et al. 2006, 2007, 2009a). These data have been used to homogeneously reassess and interpret the properties of the

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[1] See e.g. table at http://www.exoplanet.eu

entire list of transiting planets (Torres et al. 2008; Southworth 2008, 2009). However, it is difficult to take into account the underlying stellar parameters in a uniform way. Torres et al. (2008) note that measurements for the same star may not agree, and that systematic errors may be present, which are treated differently. They decided to critically reassess the values and their error bars based on the information given in the literature.

Systematics may result from, e.g., issues of data reduction, the choice of different analysis tools, line lists, and oscillator strengths. From Galactic studies, it is well known that different spectroscopic studies of the same stars do not necessarily provide consistent stellar parameters and abundances, as is also found in extra-solar planet research, e.g., the case of OGLE-TR-10 (Ammler-von Eiff & Santos 2008). At the same time, published error bars do not necessarily account for the systematics involved and usually underestimate the true uncertainties. The reader is referred to the discussion in Torres et al. (2008) and references given therein, as well as to Fuhrmann (1998) and Luck & Heiter (2005).

The situation is improved by a homogeneous spectroscopic analysis that is as accurate as possible for the entire sample of parent stars. Santos et al. (2006b) studied the host stars OGLE-TR-10, 56, 11, 113, and TrES-1. Based on high-resolution spectra with a signal-to-noise ratio of at least $\approx$100, they measured equivalent widths of lines of neutral (Fe I) and ionized iron (Fe II). Imposing the excitation and ionization equilibrium, they derived effective temperature, surface gravity, and iron abundance [Fe/H].

The goal of this work is two-fold and continues the work of Santos et al. (2006b). Firstly, accurate stellar parameters of the host stars of 13 transiting planets are derived homogeneously and combined with previous measurements for 11 further host stars, measurements that were obtained in the same way. Therefore, this work presents an extensive data set of homogeneously derived stellar parameters and iron abundances of parent stars of transiting planets. Secondly, the metallicity distribution of stars harbouring transiting planets is readdressed using the new homogeneous compilation of iron abundances.

In addition, all available spectroscopic parameters of known host stars of transiting planets are compiled, providing a possible starting point for future studies of the properties of planets and their host stars, particularly those that involve chemical abundances.

2. Observations and data reduction

High resolution spectra of six stars were obtained by the SARG spectrograph at the TNG, La Palma, and of six additional stars with SOPHIE at the OHP, France. In addition, UVES spectra of one more star, CoRoT-Exo-2, were taken from the ESO archive. The data were reduced in different ways, as explained in detail below. Afterwards, radial velocity shifts were corrected using the IRAF[2] task DOPCOR and individual exposures were added using the task SCOMBINE.

2.1. SARG

The spectral resolving power of the SARG spectra is $\frac{\lambda}{\Delta\lambda} \approx$ 57 000. The configuration of SARG comprises the yellow grism

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[2] IRAF is distributed by National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation, USA.

Table 1. Observations log.

Target	Instrument	t_{exp}[s]	S/N
CoRoT-Exo-2	UVES	2400	200
HAT-P-1	SARG	18 000	210
HAT-P-2	SARG	7200	340
HAT-P-4	SOPHIE	11 000	80
HAT-P-6	SOPHIE	18 000	180
HAT-P-7	SOPHIE	14 400	150
HD 17156	SOPHIE	3600	220
HD 149026	SARG	7200	420
TrES-2	SARG	21 600	200
TrES-3	SARG	28 800	100
TrES-4	SOPHIE	14 400	90
XO-1	SARG	25 200	170
XO-2	SOPHIE	18 000	110

Only the total exposure times are given. The exposure times of the coadded individual spectra are mentioned in the text.

and the yellow rejection filter covering the wavelength range 4650–7920 Å. However, there is a gap at 6110–6350 Å, since the mosaic detector consists of two CCD's with 2K × 4K pixels. A read-out binning of 2 × 1 was chosen. The observations were carried out during July 21–24, 2007. For every star, several spectra each with an exposure time of 1800 s were taken. Table 1 lists the total exposure time for each star. The individual SARG frames were reduced with the IRAF tasks APALL, DISPCOR, and ECIDENTIFY. All spectra are of high signal-to-noise ratio of at least 100 as measured in small spectral windows between 6420 and 6430 Å.

2.2. SOPHIE

The spectral resolving power of SOPHIE (Perruchot et al. 2008) is somewhat higher using the high-resolution mode ($\frac{\lambda}{\Delta\lambda} \approx$ 75 000) and covers a wavelength range of 3870–6940 Å. The observations were carried out during Oct. 26–28, 2008 and were affected by variable conditions. It was still possible to subtract the background by using the second fiber that was targeted at a sky position. Typical exposure times of 1800 s and 3600 s were used for individual frames. Table 1 again indicates the total exposure time for each star. The SOPHIE spectra were reduced with the on-site reduction pipeline using optimal extraction. The signal-to-noise ratios provided in the table were calculated by adding in quadrature the values given by the pipeline reduction for each individual frame. The signal-to-noise ratio achieved was generally lower than in the case of the SARG spectra but still of the order of 100 and higher.

2.3. UVES

Two spectra each with exposure times of 1200 s were acquired for CoRoT-Exo-2 with UVES (Dekker et al. 2000) on Oct. 13, 2007. The cross-disperser #3 with a central wavelength of 580.0 nm was used providing a wavelength coverage of 4200−6800 Å. A slit width of 0.''7 and a binning of 1 × 1 was chosen implying a resolving power of about 60 000. These observations form part of the programme ID 080.C-0661 and were retrieved from the ESO archive. The raw data were reduced with a locally installed version (2.9.7) of the reduction pipeline in combination with the MIDAS version 07SEPpl1.1. The red arm

spectra of both the upper and lower CCD were optimally extracted, preserving the wavelength range. A section of 70 Å is missing at the central wavelength because of the gap between the two detectors. The signal-to-noise ratio given in Table 1 was estimated in the same way as for the SARG spectra.

3. Derivation of stellar parameters and metallicity

The work of Santos et al. (2006b) is extended consistently by analysing the spectra in the same way as described in Santos et al. (2004). In brief, the analysis begins with the selection of weak iron lines from a list of 39 Fe I and 16 Fe II lines. While SOPHIE and UVES detect almost all lines in this list, the detector gap of the SARG spectrograph happens to correspond to a wavelength region that is rich in useful Fe lines. Therefore, the analysis of the SARG spectra has to rely typically on only 20 Fe I lines and 9 Fe II lines.

Equivalent widths were measured with the IRAF SPLOT task contained in the ECHELLE package. Effective temperature, surface gravity, and iron abundance [Fe/H] were derived for local thermal equilibrium by assuming iron excitation and ionization equilibrium. The correct value of the microturbulence parameter was chosen by ensuring that [Fe/H] does not vary with reduced equivalent width. The procedure is based on the use of the 2002 version of MOOG[3] (Sneden 1973) and ATLAS plane-parallel model atmospheres (Kurucz 1993).

Error bars were derived in the same way as described in Santos et al. (2004) and Santos et al. (2006b), who follow the method of Gonzalez & Lambert (1996) and Gonzalez & Vanture (1998). The error bars are purely statistical, consisting of the dispersion in the iron abundances as measured from each iron line, as well as the uncertainties in the slopes of the correlations of iron abundance with reduced equivalent width, excitation, and ionization potential.

The derived stellar parameters are presented in the upper part of Table 2, which in addition includes data for stars harbouring transiting planets analysed by the same method. In the lower part of the table, all other host stars of transiting planets[4] with available abundance information are compiled. Preference is given to spectroscopically measured effective temperatures and surface gravities, since these represent the basis of spectroscopic abundance measurements. In some cases however, the analysis was not based exclusively on spectroscopic data. The most reliable spectroscopic metallicity measurements are compiled for future work, e.g., studies of correlations of planetary properties with the properties of the parent stars.

4. Comparison with previous measurements

Torres et al. (2008) compiled literature values for host stars of transiting planets, including those in the present work. To refine planetary parameters, Torres et al. (2008) revised the stellar data from the literature. In contrast, the present work aims to provide an improved set of stellar parameters based on spectroscopy, then compare with previous determinations. The remarks made by Torres et al. (2008) concerning the limits of this comparison have to be taken into account. In this respect, a discussion of the spectroscopic techniques will be important.

The parameters are compared with those determined by other groups (Table 3). The comparison is restricted to spectral

synthesis studies, although other measurements may have been determined by other methods. For example, in the case of HD 149026, the semi-empirical temperature determination of Masana et al. (2006) of 6183 ± 57 K agrees well with the spectroscopic measurements. Consistent results are also obtained by Robinson et al. (2007) using Lick indices ($T_{\rm eff}$ = 6081 K, log g = 4.24, [Fe/H] = 0.32), although they state that these parameters are beyond any of the tested ranges.

4.1. Only few different techniques

In terms of the methods used for spectroscopic analysis, the previous studies are very homogeneous, i.e., only a few different techniques were used by all groups. Bakos et al. (2007b), Bakos et al. (2007a), Burke et al. (2007), Fischer et al. (2007), Kovács et al. (2007), McCullough et al. (2006), Noyes et al. (2008), Pál et al. (2008), and Sato et al. (2005) all of which are referred to Valenti & Fischer (2005), mostly explicitly state the use of the SME (Spectroscopy Made Easy) software (Valenti & Piskunov 1996), which is based on ATLAS model atmospheres. This spectral fitting technique varies the stellar parameters and the abundances of some species to minimize the differences between the synthetic spectra and observed spectrum. Kovács et al. (2007), Noyes et al. (2008), and Pál et al. (2008) refined surface gravity using model isochrones and repeated the analysis iteratively as required. Bouchy et al. (2008) also applied a spectral fitting technique, using MARCS model atmospheres.

The approach of Sozzetti et al. (2007, 2009a), however, is very similar to the present work imposing the Fe I/II ionization and excitation equilibria using the MOOG line formation code and ATLAS model atmospheres. A different technique was used by Loeillet et al. (2008), who analysed the spectra based on a cross-correlation technique following Santos et al. (2002).

Some groups supplement their measurements with results from other techniques, e.g., using Hα and line depth ratios (Bouchy et al. 2008; Sozzetti et al. 2007, 2009a).

4.2. Small amount of variety between spectrographs used

The spectra used by the different groups to derive stellar parameters were taken with different instruments, and had different spectral resolutions and signal-to-noise ratios. Large differences because of the use of different instruments are not expected, since all are Échelle spectrographs with high resolving powers. Half of the studies mentioned in Table 3 are based on spectra taken with the Keck HIRES spectrograph, although with slightly different configurations. Bakos et al. (2007b), Bakos et al. (2007a), Kovács et al. (2007), Noyes et al. (2008), and Pál et al. (2008) obtained Keck HIRES spectra with a resolving power of $\frac{\lambda}{\Delta\lambda}$ = 55 000, while the HIRES spectra used by Sozzetti et al. (2007, 2009a) have $\frac{\lambda}{\Delta\lambda}$ = 71 000. Burke et al. (2007) and McCullough et al. (2006) obtained spectra with $\frac{\lambda}{\Delta\lambda}$ = 60 000 with the Échelle spectrograph at the Harlan J. Smith telescope. The results of Sato et al. (2005) are based on SUBARU HDS spectra with $\frac{\lambda}{\Delta\lambda}$ = 55 000. The spectra analysed by Loeillet et al. (2008) were obtained with the SOPHIE spectrograph.

A comparison of the signal-to-noise ratios is not possible since most groups do not explicitly state the precise values. Sato et al. (2005) indicate a typical value of ≈150/pix at 5500 Å for all their stars. The HARPS spectra used by Bouchy et al. (2008) have a signal-to-noise ratio of about 80/pix.

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[3] http://verdi.as.utexas.edu/moog.html
[4] According to http:www.exoplanet.eu.

Table 2. Stellar parameters and iron abundance of host stars of transiting planets.

Star	$T_{\rm eff}$ [K]	$\log g$ (cgs)	ξ_t [km s^{-1}]	[Fe/H]	N(Fe I, Fe II)		σ(Fe I, Fe II)	Source
CoRoT-Exo-2	5608 ± 37	4.71 ± 0.20	1.49 ± 0.06	0.07 ± 0.04	26,	9	0.03, 0.09	this work
HAT-P-1	6076 ± 27	4.47 ± 0.07	1.17 ± 0.05	0.21 ± 0.03	21,	10	0.02, 0.03	this work
HAT-P-2	6951 ± 181	4.45 ± 0.08	1.61 ± 0.33	0.49 ± 0.12	14,	8	0.06, 0.03	this work
HAT-P-4	6054 ± 60	4.17 ± 0.28	1.59 ± 0.09	0.35 ± 0.08	30,	9	0.06, 0.12	this work
HAT-P-6	6855 ± 111	4.69 ± 0.20	2.85 ± 1.15	−0.08 ± 0.11	21,	9	0.07, 0.07	this work
HAT-P-7	6525 ± 61	4.09 ± 0.08	1.78 ± 0.14	0.31 ± 0.07	33,	10	0.06, 0.03	this work
HD 17156	6084 ± 29	4.33 ± 0.05	1.47 ± 0.05	0.23 ± 0.04	30,	10	0.03, 0.02	this work
HD 80606	5574 ± 72	4.46 ± 0.20	1.14 ± 0.09	0.32 ± 0.09	38,	5	0.07, 0.08	Santos et al. (2004)
HD 149026	6162 ± 41	4.37 ± 0.10	1.41 ± 0.07	0.36 ± 0.05	23,	9	0.04, 0.04	this work
HD 189733	5050 ± 50	4.53 ± 0.14	0.95 ± 0.07	−0.03 ± 0.04	−,	−	−, −	Bouchy et al. (2005)
HD 209458	6117 ± 26	4.48 ± 0.08	1.40 ± 0.06	0.02 ± 0.03	−,	−	−, −	Santos et al. (2004)
OGLE-TR-10	6075 ± 86	4.54 ± 0.15	1.45 ± 0.14	0.28 ± 0.10	33,	11	0.08, 0.06	Santos et al. (2006b)
OGLE-TR-56	6119 ± 62	4.21 ± 0.19	1.48 ± 0.11	0.25 ± 0.08	31,	9	0.06, 0.08	Santos et al. (2006b)
OGLE-TR-111	5044 ± 83	4.51 ± 0.36	1.14 ± 0.10	0.19 ± 0.07	31,	7	0.07, 0.18	Santos et al. (2006b)
OGLE-TR-113	4804 ± 106	4.52 ± 0.26	0.90 ± 0.18	0.15 ± 0.10	30,	5	0.10, 0.09	Santos et al. (2006b)
OGLE-TR-132	6411 ± 179	4.86 ± 0.14	1.46 ± 0.36	0.43 ± 0.18	−,	−	−,−	Bouchy et al. (2004)
OGLE-TR-182	5924 ± 64	4.47 ± 0.18	−	0.37 ± 0.08	−,	−	−, −	Pont et al. (2008)
OGLE-TR-211	6325 ± 91	4.22 ± 0.17	1.63 ± 0.21	0.11 ± 0.10	−,	−	−, −	Udalski et al. (2008)
TrES-1	5226 ± 38	4.40 ± 0.10	0.90 ± 0.05	0.06 ± 0.05	36,	7	0.04, 0.05	Santos et al. (2006b)
TrES-2	5795 ± 73	4.30 ± 0.13	0.79 ± 0.12	0.06 ± 0.08	20,	9	0.06, 0.05	this work
TrES-3	5502 ± 157	4.44 ± 0.22	1.00 ± 0.30	−0.10 ± 0.19	20,	8	0.14, 0.07	this work
TrES-4	6293 ± 96	4.20 ± 0.27	2.01 ± 0.17	0.34 ± 0.10	27,	10	0.07, 0.11	this work
XO-1	5754 ± 42	4.61 ± 0.05	1.07 ± 0.09	−0.01 ± 0.05	21,	9	0.04, 0.02	this work
XO-2	5350 ± 72	4.14 ± 0.22	1.10 ± 0.08	0.42 ± 0.07	22,	9	0.05, 0.10	this work
CoRoT-Exo-1	5950 ± 150	4.25 ± 0.30		−0.3 ± 0.25[a]				Barge et al. (2008)
CoRoT-Exo-3	6740 ± 140	4.22 ± 0.07		0.02 ± 0.06[f]				Deleuil et al. (2008)
CoRoT-Exo-4	6190 ± 60	4.41 ± 0.05	0.94 ± 0.07	0.05 ± 0.07[a]				Moutou et al. (2008)
GJ 436	3350 ± 300	5.0		−0.02 ± 0.20[e]				Bonfils et al. (2005); Maness et al. (2007)
HAT-P-3	5185 ± 46	4.61 ± 0.05		0.27 ± 0.04				Torres et al. (2007)
HAT-P-5	5960 ± 100	4.368 ± 0.028		0.24 ± 0.15				Bakos et al. (2007c)
HAT-P-8	6200 ± 80	4.15 ± 0.03		0.01 ± 0.08				Latham et al. (2008)
HAT-P-9	6350 ± 150	$4.29^{+0.03}_{-0.04}$		0.12 ± 0.20				Shporer et al. (2009)
HAT-P-11	4780 ± 50	4.59 ± 0.03		0.31 ± 0.05				Bakos et al. (2009b)
OGLE2-TR-L9	6933 ± 58	4.47 ± 0.13		−0.05 ± 0.20				Snellen et al. (2009)
WASP-1	6110 ± 45	4.28 ± 0.15		0.26 ± 0.03[b]				Stempels et al. (2007)
WASP-2	5200 ± 200	4.3 ± 0.3		0.1 ± 0.2				Cameron et al. (2007)
WASP-3	6400 ± 100	4.25 ± 0.05		0.00 ± 0.20[a]				Pollacco et al. (2008)
WASP-4	5500 ± 150	4.3 ± 0.2		0.0 ± 0.2[a]				Wilson et al. (2008)
WASP-5	5700 ± 150	4.3 ± 0.2		0.0 ± 0.2[a]				Anderson et al. (2008)
WASP-6	5450 ± 100	4.6 ± 0.2	1.0 ± 0.2	−0.20 ± 0.09				Gillon et al. (2009)
WASP-7	6400 ± 100	4.3 ± 0.2	1.5 ± 0.2	0.0 ± 0.1				Hellier et al. (2009)
WASP-10	4675 ± 100	4.40 ± 0.20		0.03 ± 0.20[a]				Christian et al. (2009)
WASP-11/HAT-P-10	4980 ± 60	4.54 ± 0.03		0.13 ± 0.08				Bakos et al. (2009a)
WASP-12	6300^{+200}_{-100}	4.38 ± 0.10		$0.30^{+0.05}_{-0.15}$[a]				Hebb et al. (2009)
WASP-13	5826 ± 100	4.04 ± 0.2		0.0 ± 0.2[a]				Skillen et al. (2009)
WASP-14	6475 ± 100	4.07 ± 0.20		0.0 ± 0.2[a]				Joshi et al. (2009)
WASP-15	6300 ± 100	4.35 ± 0.15	1.4 ± 0.1	−0.17 ± 0.11				West et al. (2009)
XO-3	6429 ± 100	4.244 ± 0.041		−0.177 ± 0.080[c]				Winn et al. (2008), updating Johns-Krull et al. (2008)
XO-4	6397 ± 70	4.18 ± 0.07		−0.04 ± 0.03[d]				McCullough et al. (2008)
XO-5	5510 ± 44	4.52 ± 0.06		0.25 ± 0.03				Burke et al. (2008)
XO-5	5370 ± 70	4.31 ± 0.03		0.05 ± 0.06				Pál et al. (2009)

The upper part of the table lists the parameters homogeneously derived using the method of Santos et al. (2004). The lower part contains data for all host stars of transiting planets not studied in this work but with stellar parameters and iron abundance or metallicity published elsewhere. [a] The cited value gives overall metallicity [M/H] rather than [Fe/H]. [b] They provide a value for overall metallicity of 0.23 ± 0.08. [c] They provide a value for overall metallicity of −0.204 ± 0.023. [d] They provide a value for overall metallicity of −0.02 ± 0.05. [e] The average of the values given by Bonfils et al. (2005) and Maness et al. (2007) is adopted here. [f] The abundance derived from Fe II lines is given. Deleuil et al. (2008) infer an overall metallicity of [M/H] = −0.02 ± 0.06.

Sozzetti et al. (2007) obtained an average of 120/pix for TrES-2, while Sozzetti et al. (2009a) achieved 100/pix.

The present work is based on spectra of high signal-to-noise ratio that were observed, reduced, and analysed in the same way. Therefore, the new results allow us to check the consistency of previously obtained results.

4.3. Systematics and possible explanations

In general, the new results are consistent with previous measurements as can be realized from a comparison of Tables 2 and 3 (see Fig. 1 for graphical representations). Only the properties of HAT-P-2 appear discrepant to a very significant extent. While

Table 3. Stellar parameters and metallicities previously derived by spectroscopy.

Star	$T_{\rm eff}$ [K]	$\log g$ (cgs)	$\xi_{\rm t}$ [km s^{-1}]	[Fe/H]	Source	[Fe/H] (this work)
CoRoT-Exo-2	5625 ± 120	4.3 ± 0.2	–	0.0 ± 0.1	Bouchy et al. (2008)	+0.07 ± 0.04
HAT-P-1	5795 ± 45	4.45 ± 0.06	–	+0.13 ± 0.02	Bakos et al. (2007b)	+0.21 ± 0.03
HAT-P-2	6290 ± 110	4.22 ± 0.14	–	+0.12 ± 0.08	Bakos et al. (2007a)	+0.49 ± 0.12
	–	–	–	+0.11 ± 0.10	Loeillet et al. (2008)	
HAT-P-4	6032 ± 80	4.36 ± 0.11	–	+0.32 ± 0.08	Kovács et al. (2007)	
	5860 ± 80	$4.14^{+0.01}_{-0.04}$	–	+0.24 ± 0.08	Kovács et al. (2007, using isochrones)	+0.35 ± 0.08
HAT-P-6	6353 ± 88	3.84 ± 0.12	–	−0.23 ± 0.08	Noyes et al. (2008)	
	6570 ± 80	4.22 ± 0.03	–	−0.13 ± 0.08	Noyes et al. (2008, using isochrones)	−0.08 ± 0.11
HAT-P-7	6350 ± 80	4.06 ± 0.10[a]	–	+0.26 ± 0.08	Pál et al. (2008)	+0.31 ± 0.07
HD 17156	6079 ± 56	4.29 ± 0.06	–	+0.24 ± 0.03	Fischer et al. (2007)	+0.23 ± 0.04
HD 149026	6147 ± 50	4.26 ± 0.07	–	+0.36 ± 0.05	Sato et al. (2005)	+0.36 ± 0.05
TrES-2	5850 ± 50	4.4 ± 0.1	1.00 ± 0.05	−0.15 ± 0.10	Sozzetti et al. (2007)	+0.06 ± 0.08
TrES-3	5650 ± 75	4.4 ± 0.1	0.85 ± 0.05	−0.19 ± 0.08	Sozzetti et al. (2009a)	−0.10 ± 0.19
TrES-4	6200 ± 75	4.0 ± 0.1	1.50 ± 0.05	+0.14 ± 0.09	Sozzetti et al. (2009a)	+0.34 ± 0.10
XO-1	5750 ± 13	4.53 ± 0.065	–	+0.015 ± 0.04	McCullough et al. (2006)	−0.01 ± 0.05
XO-2	5340 ± 32	4.48 ± 0.05	–	+0.45 ± 0.02	Burke et al. (2007)	+0.42 ± 0.07

Only the stars analysed in the present work are listed. The last column repeats the values from Table 2 to facilitate the comparison. [a] Virtually identical to the value of $4.07^{+0.04}_{-0.08}$ derived using isochrones.

Bakos et al. (2007a) derived an effective temperature of 6290 K for HAT-P-2 and an iron abundance of 0.12 dex, the present work infers a temperature that is higher by 700 K and an iron abundance of 0.49 dex (see Figs. 1a and d). When considering the formal error bars of HAT-P-1, both effective temperature and iron abundance appear to be in disagreement, while surface gravity agrees. In this particular case, the formal error bars almost certainly underestimate the true uncertainties. Although this implies that all stellar parameter measurements of HAT-P-1 could be in closer agreement, the offsets between given pairs of measurements are found to be systematic for all HAT objects.

We admit that there may be problems with Fe I at effective temperatures higher than ≈6500 K, which may cause an overestimation of effective temperature. We note, however, that the previously derived effective temperatures of all the HAT host stars are systematically lower than the values of the present work, even at solar temperatures. At this point, one realizes that all HAT host stars were observed with the same Keck HIRES configuration and were analysed with the same spectral fitting technique. Taking into account possible systematics in the previous analyses as well as in the present work, we thus conclude that the true effective temperature of HAT-P-2 and HAT-P-6 will be somewhat higher than the previous measurements, but not as high as the values derived in the present work.

The iron abundance, which is the quantity primarily addressed by the present work, is also affected by systematics. The previously measured abundances of the HAT objects are systematically lower. In abundance analyses it is common for the origin of these discrepancies to be almost unidentifiable. In the present case, one may only conclude that it is not caused entirely by the use of different analysis packages. If this would be the case, similar deviations would also be expected for some of the abundance data represented by crosses in Fig. 1. As for the HAT objects, some of these are also based on the approach of Valenti & Fischer (2005) but perfectly agree with the present work.

The consideration of the TrES objects (Fig. 1, squares) also shows that the situation might be more complicated, since Sozzetti et al. (2007, 2009a) analysed the TrES stars essentially the same way as in the present work, but using Keck HIRES spectra with a higher spectral resolution than in previous studies of the HAT stars. Inspection of Figs. 1a and b shows that the previously derived stellar parameters of the TrES objects are in

only slightly closer agreement with the present work than the literature values of the HAT objects. As for the HAT objects, the abundance determinations of Sozzetti et al. (2007) and Sozzetti et al. (2009a) are systematically lower than those derived in the present work using the methods of Santos et al. (2006b). This is true not only for TrES-2, 3, 4 but also for TrES-1, which was studied by Sozzetti et al. (2006) and Santos et al. (2006b).

In general, discrepancies in surface gravity hardly affect iron abundance as long as effective temperatures are in agreement. This is exemplified markedly by HAT-P-2, HAT-P-6, CoRoT-Exo-2, and XO-2 in Fig. 1. On the one hand, the reader may note a substantial difference in surface gravity for the last three objects (Fig. 1b). However, there are far fewer discrepancies and even close agreement between the different values of temperature and iron abundance. On the other hand, HAT-P-2, which exhibits the greatest variation in its values of abundance, also exhibits the greatest variation in the measurements of effective temperature. While the iron abundances are found to be relatively insensitive to variations in surface gravity, the planetary parameters are usually not found to be so insensitive when the surface gravity of the host stars is used to derive them. This particular problem is overcome by applying the mean stellar density from the transit light curves (e.g., Sozzetti et al. 2007; Holman et al. 2007; Torres et al. 2008), thus avoiding the use of highly uncertain spectroscopic surface gravities. This workaround is not possible in abundance analysis and therefore, the present work addresses spectroscopic surface gravities whenever possible. The determination of chemical abundance is closely tied to the adopted values of effective temperature and surface gravity. Stellar parameters and abundances must fulfil the requirements of ionization and excitation equilibria in a consistent way. The unverified adoption of external values of effective temperatures (e.g., from colour index calibrations) or surface gravities (e.g., from evolutionary models) may lead to spurious abundances (Affer et al. 2005; Luck & Heiter 2005).

5. The metallicity distribution of stars harbouring transiting planets

The results of the present work are now combined with previous analyses of host stars of transiting planets completed using the methods of Santos et al. (2004) (upper part of Table 2). Figure 2
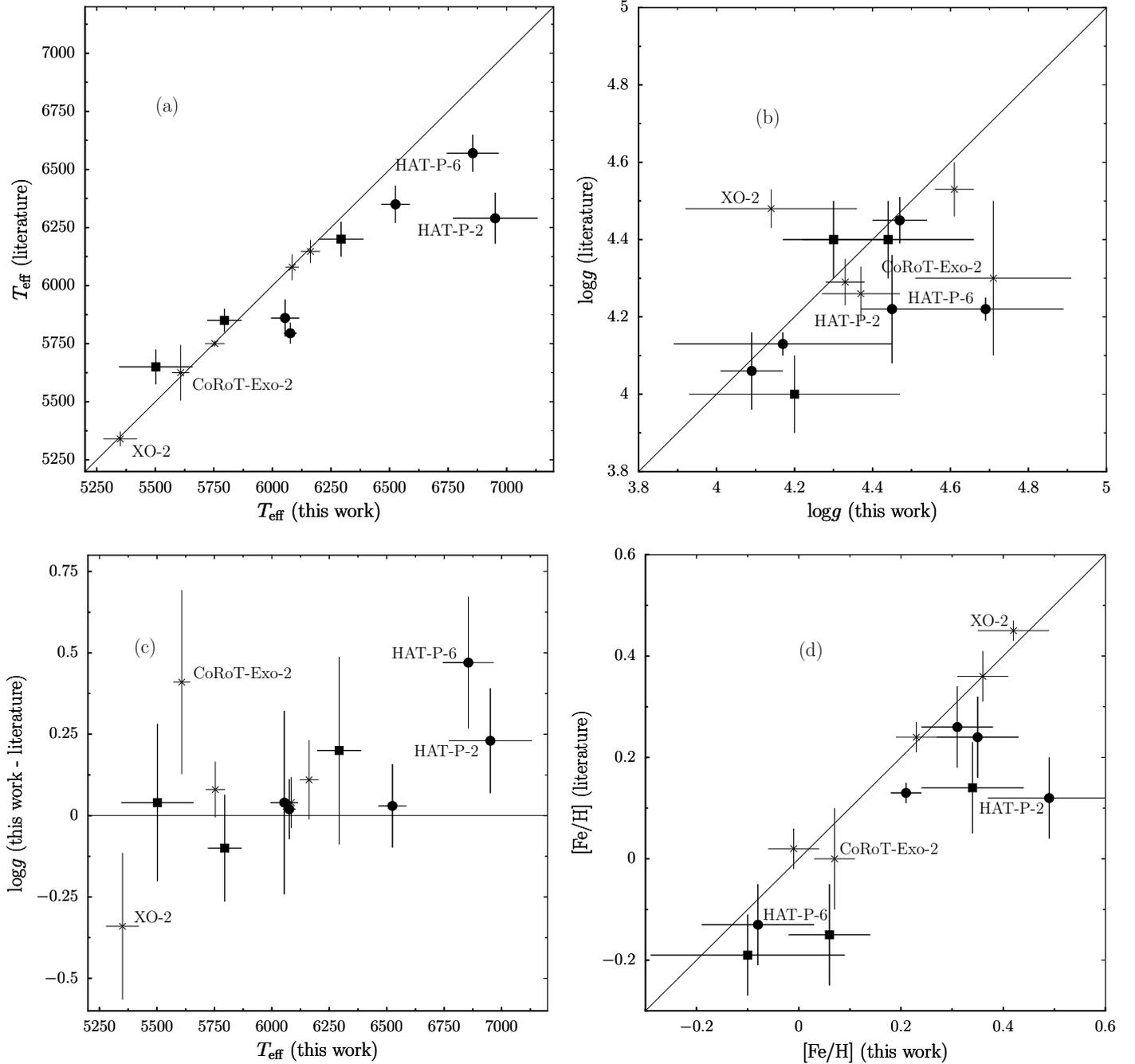
Fig. 1. Comparison with previous work. Stellar parameters and iron abundance derived in the present work are compared with literature values. HAT objects are indicated by filled circles and TrES objects by squares. All other objects are depicted by crosses. Identity is marked by the solid line. Labelled data points are extensively discussed in the text. **a)** Effective temperatures obtained in the present work are compared with literature values. **b)** Surface gravities derived in the present work are compared with literature values. **c)** Residual surface gravities are displayed with respect to effective temperature. **d)** Iron abundance inferred in the present work are compared with literature values.

compares the distribution of iron abundance [Fe/H] for three different samples: the distribution for the stars with planets from Santos et al. (2004), for a comparison sample of stars without planets (Santos et al. 2004, 2005), and for the data of stars hosting transit planets. The distribution of the transit-planet host stars coincides well with the distribution of stars with planets from Santos et al. (2004). There could be a slight shift in the data for transit-planet host stars towards higher abundance[5]. However,

the p-value of a K-S test is 0.27, which is consistent with the samples being drawn from the same distribution. One may note that the distribution of stars harbouring transiting planets does not show a tail towards low metallicities. This difference is not detected by the K-S test, which is less sensitive at the ends of the distributions. Still, the lack of a tail is not significant here because of the small number of measurements.

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[5] In a discussion of the OGLE objects, Sozzetti (2004) and Santos et al. (2006a,b) already noted the large distance of most of these objects,

sampling Galactic regions of a possibly higher overall metallicity. The verification of this effect would require the analysis of many stars without planets in the same galactic regions.
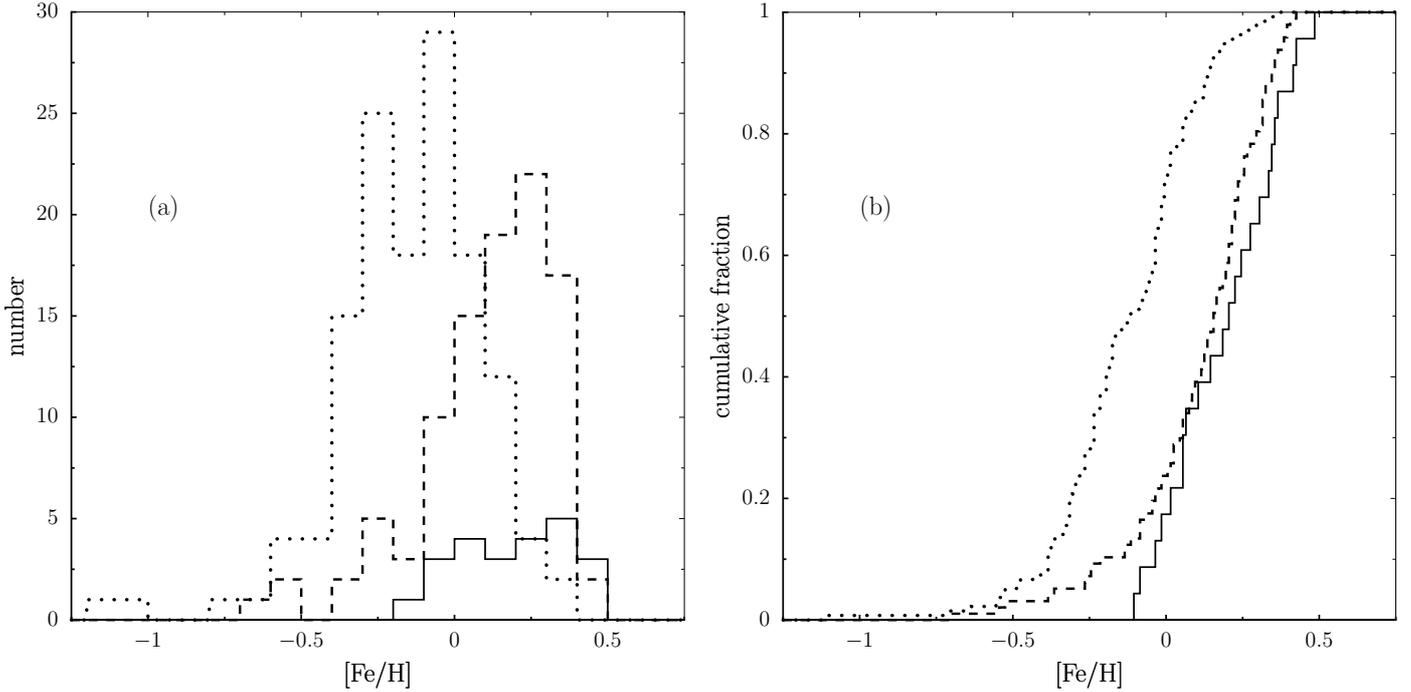
Fig. 2. Comparison of the distribution of [Fe/H] of stars with and without planets. **a)** The histogram displays the distribution of the stars with planets (Santos et al. 2004; dashed), the stars with transiting planets (upper part of Table 2; solid), compared to a sample of stars without planets (Santos et al. 2004, 2005; dotted). **b)** The cumulative fraction is shown with the same line styles as in **a)**.

A comparison of the present work with the work of Santos et al. (2004) can be completed accurately in a relative sense. All data shown in Fig. 2 were derived using the same spectroscopic techniques. Therefore, any systematic offsets caused by different methods of analysis are not expected here.

6. Summary and discussion

We have derived the stellar parameters and iron abundances of 13 host stars of transiting planets. The analysed data consist of spectra obtained with the SARG, SOPHIE, and UVES spectrographs, and were analysed by assuming the iron ionization and excitation equilibria.

A comparison with previous determinations reveals some discrepancies between different values of effective temperatures and surface gravities, which are most striking in the cases of CoRoT-Exo-2, HAT-P-2, HAT-P-6, and XO-2. Systematics are also noted for the iron abundance measurements – a finding which cannot easily be explained. Previous abundance measurements for the HAT and the TrES objects are systematically lower, while the data for other stars are in agreement with the present work. In general, abundances are found to be very robust with respect to possible uncertainties in surface gravity.

Although uniform data sets such as the literature data of the HAT and TrES objects as well as the present work principally allow one to address the origin of systematic discrepancies, this cannot be easily accomplished in the present case. The effects of instrumental configuration, reduction techniques, choice of atmospheric parameters, and line lists, cannot be determined separately with the available data sets.

The inferred iron abundance is affected most substantially in the case of HAT-P-2 (also known as HD 147506), which also shows the largest temperature discrepancies. This is particularly interesting because the ~ 8 $M_{\rm Jup}$ planetary companion has been shown to be anomalously small, with models fitting the inferred planetary radius yielding suprisingly large enrichments in heavy elements (above 200 $M_\oplus$; Baraffe et al. 2008). The accretion of such a high mass in heavy elements is difficult to explain with present formation models (see e.g., Ikoma et al. 2006). The improved effective temperature and metallicity of the parent star found here opens up the possibility that updated stellar parameters accounting for the new measurements yield a planetary radius that is closer to expectations.

Extending the work of Santos et al. (2006b), an extensive compilation of homogeneously derived effective temperatures, surface gravities, and iron abundances of 24 stars harbouring transiting planets is now available. Therefore, the distribution of the iron abundances can be compared very accurately in a relative sense, to the distribution of a large sample of planet host stars presented in Santos et al. (2004). The distributions are consistent with being drawn from the same population. The uniform data presented in this paper can be used for further statistical studies of the properties of transiting planet-host stars, and to refine a sample of uniform paramaters for the planets. This work will be the subject of a forthcoming paper.

The dataset was supplemented by spectroscopic parameters and in particular the iron abundance of 26 additional objects, thus comprising spectroscopic data of 50 host stars of transiting planets. Such a compilation is important to future planet studies involving abundance measurements of the host stars.

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