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The *Kepler* Smear Campaign I: An Asteroseismic Catalogue of Bright Red Giants

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ABSTRACT

Here we present the first data release of the *Kepler* Smear Campaign, using collateral 'smear' data obtained by *Kepler* to reconstruct light curves of 101 stars too bright to have been otherwise observed. We describe the pipeline developed to extract and calibrate these light curves, and show that we attain photometric precision comparable to stars ordinarily more observed in the nominal *Kepler* mission. In this Paper, we focus in particular on a subset of these consisting of 60 red giants for which we detect solar-like oscillations. Using high-resolution spectroscopy from the Tillinghast Reflector Échelle Spectrograph (TRES) together with asteroseismic modelling, we constrain the masses and evolutionary states of these benchmark red giants. All source code, light curves, TRES spectra, and asteroseismic and stellar parameters are publicly available as a *Kepler* legacy sample.

Key words: asteroseismology – techniques: photometric – stars: variable: general

1 INTRODUCTION

The *Kepler* Space Telescope, operated by NASA, was launched in 2009 to obtain photometry of hundreds of thousands of stars in a field in Cygnus-Lyra, in order to detect a statistically-useful sample of transiting exoplanets (Borucki et al. 2010). It achieved this primary goal, showing that exoplanets are common around Sun-like stars (Fressin et al. 2013; Petigura et al. 2013; Foreman-Mackey et al. 2014), though with the failure of two reaction wheels, the mission was cut short and there remain substantial uncertainties on these estimates. *Kepler* was revived as a two-wheeled mission, K2, with its third axis balanced against solar radiation pressure. K2 is therefore constrained to point in the ecliptic plane, which it surveys in a succession of $\sim$ 80 day Campaigns. In this paper, we will deal exclusively with data from the nominal *Kepler* mission before this change.

Beyond searching for planets, *Kepler* has revolutionized the field of asteroseismology (Gilliland et al. 2010). It has yielded the first detection of gravity-mode period spacings in a red giant (Beck et al. 2011), enabling probes of interior rotation of red giants (Beck et al. 2012) and distinguishing between hydrogen- and helium-burning cores (Bedding et al. 2011). It has also permitted the determination of ages and fundamental parameters of main-sequence stars (Silva Aguirre et al. 2013), including planet-hosting stars (Huber et al. 2013; Silva Aguirre et al. 2015; Van Eylen et al. 2018), revealing the most ancient known planetary system, dating back to the earliest stages of the galaxy (Campante et al. 2015). By comparing asteroseismic stellar ages to stellar rotation periods, Angus et al. (2015) have shown that gyrochronology models cannot fit the data with a single relation, leading van Saders et al. (2016) to suggest a qualitative change in dynamo mechanism as stars age through the main sequence.

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A major outcome of the *Kepler* asteroseismology programme is a legacy sample of extremely well characterized stars which can serve as benchmarks for future work (Lund et al. 2016; Silva Aguirre et al. 2016). As well as asteroseismology, by also using optical interferometry, it has been possible to determine fundamental parameters of main-sequence and giant stars with unprecedented precision (Huber et al. 2012; White et al. 2013, 2015). Likewise by combining with spectroscopy, Hawkins et al. (2016c) have been able to produce a large sample of stars with precise elemental abundances by fitting spectroscopic data with $\log g$ and $T_{\rm eff}$ fixed to asteroseismically-determined values. It is necessary to calibrate such a study against benchmark stars with very precisely-determined parameters, which in practice means requires nearby bright stars that are amenable to very high signal-to-noise spectroscopy plus asteroseismology (Creevey et al. 2013), parallaxes (Hawkins et al. 2016a), and/or interferometry (Casagrande et al. 2014; Creevey et al. 2015). This is especially important in the context of the *Gaia* mission (Gaia Collaboration et al. 2016), which has recently put out its second data release of 1,692,919,135 sources, including 1,331,909,727 with parallaxes (Gaia Collaboration et al. 2018). These data will form the basis of many large surveys and it is vital that they are calibrated correctly. To this end, 34 FGK stars have been chosen as *Gaia*-ESO benchmark stars for which metallicities (Jofré et al. 2014), effective temperatures and surface gravities (Heiter et al. 2015), and relative abundances of α and iron-peak elements (Jofré et al. 2015) have been determined. This has been accompanied by the release of high resolution spectra (Blanco-Cuaresma et al. 2014) and formed the basis of extensions to lower metallicities (Hawkins et al. 2016b), stellar twin studies (Jofré 2016) and comparisons of stellar abundance determination pipelines (Jofré et al. 2017).

Brighter *Kepler* stars are therefore ideal benchmark targets, as photometry can be most easily complemented by *Hipparcos* parallaxes, interferometric diameters, and high resolution spectroscopy. Unfortunately, the *Kepler* field was deliberately placed to minimize overall the number of saturated stars, so that only a dozen stars brighter than 6th magnitude landed on silicon (Koch et al. 2010). This was because stars brighter than $Kp \sim 11$ saturate the CCD detector, spilling electrons up and down their column on the CCD and rendering these pixels otherwise unusable. Furthermore, due to the limited availablility of bandwidth to download data from the satellite, only a fraction What fraction? of pixels on the *Kepler* detector are actually downloaded, these being allocated via a competitive proposal process. The result of these two target selection constraints is that photometry was obtained for only a small number of saturated stars in the *Kepler* field, while many bright targets were ignored.

Kolodziejczak & Caldwell (2011) noted that there is a way to obtain photometry of every target on-silicon in *Kepler* using a data channel normally used for calibration, even if active pixels were not allocated and downloaded. *Kepler* employs an inter-line transfer CCD as its detector, which successively shuffles each row of pixels down to the edges of the chip where they are ultimately read out. Because the *Kepler* camera lacks a shutter, the detector is exposed to light during the readout process, with the result that fluxes in each pixel are biased up by light collected from objects in the same column. This is a particularly serious issue for faint objects in the same detector column as brighter stars, and it is important to calibrate this at each readout stage. Six rows of blank 'masked' pixels are allocated in each column to measure the smear bias; furthermore, six 'virtual' rows are recorded at the end of the readout, with the result that twelve rows of pixels sample the smear bias in each column. Kolodziejczak & Caldwell (2011) realized that these encode the light curves of bright targets in a 1D projection of the star field. The masked and virtual smear registers each receive $\sim 1/1034$ of the incident flux in each column; if this is dominated by the light from a single star, the flux combining both smear registers is equivalent to that of a star ~ 6.8 times fainter.

In Pope et al. (2016), we demonstrated a method for extracting precise light curves of bright stars in *Kepler* and K2, and presented light curves of a small number of variable stars as examples to illustrate this method. In this Paper we present light curves of all unobserved or significantly under-observed stars brighter than $V = 8$ in the *Kepler* field. This sample is biased towards red giants and hot stars, containing only a few FG dwarfs. We find no transiting planets, but detect M new eclipsing binaries, and solar-like oscillations in N red giants. We do not model hot stars or FG dwarfs in great detail, but provide some discussion and initial classification of interesting variability. For eclipsing binaries, we present the results of light-curve modelling to precisely determine their parameters. Finally, for the oscillating red giants, which constitute the bulk of the sample, we determine the asteroseismic parameters $\nu_{\rm max}$ and $\Delta\nu$, and therefore stellar masses and $\log g$ measurements; and we and obtain high-resolution spectroscopy with the Tillinghast Reflector Échelle Spectrograph (TRES), from whose spectra we derive stellar parameters and elemental abundances constrained by asteroseismic parameters. We discuss the potential for these as benchmark stars for other stellar surveys, in particular *Gaia*.

We have made all new data products and software discussed in this paper publicly available, and encourage interested readers to use these in their own research.

2 METHOD

In this Section we will discuss the methods used for characterizing our new benchmark stars. We have obtained smear light curves for our sample of red giant stars with the `keplersmear` pipeline as described in Section 2.1, performed asteroseismology on all of these to extract $\nu_{\rm max}$ and therefore $\log g$ as described in Section 2.2, and combined these with TRES spectra to obtain chemical abundances as described in Section 2.3.

2.1 Photometry

We selected as our sample all stars on-silicon in *Kepler* with $Kp < 8$ which were unobserved for more than 10 quarters Tim: what was your cutoff in quarters for 'underobserved' stars?, including those stars which were entirely unobserved. A number of these lay just at the edge of a detector, with the result that in some cadences the centroid of the star did not lie on the chip; light curves from these targets were found to be of extremely low quality and all of these objects were discarded. After applying these criteria we obtained a list of 101 targets. Aside from the restriction on stars falling on the edge of a chip, the addition of these objects to conventionally-observed stars makes the *Kepler* survey magnitude-complete down to $Kp = 8$.

In preparing light curves of the *Kepler* smear stars, we follow the methods described in Pope et al. (2016), with some improvements. We select using RA and Dec values from the *Kepler* Input Catalog (KIC) (Brown et al. 2011), and query MAST to find the corresponding mean pixel position for a given *Kepler* quarter. We measure the centroid of smear columns in the vicinity, and use these values to do raw aperture photometry. We find that the cosine-bell aperture used for raw photometry in Pope et al. (2016) can in some light curves introduce position-dependent systematics and jumps. We instead in this work apply a super-Gaussian aperture, $A \propto \exp \frac{-(x-x_0)}{w}^4$, where x_0 is the centroid and w a width in pixels. The very flat top of this function helps avoid significant variation with position, while still smoothly rolling off at the edges to avoid discontinuous artefacts. We calculate this on a grid of $10\times$ subsampled points in pixel space so that the sharply varying edge changes column weights smoothly as a function of centroid. We extract photometry using apertures with a range of widths $w \in \{1.5, 2, 3, 4, 5\}$ pixels.

From this raw photometry we subtract a background light curve, which corrects for time-varying global systematics. Whereas in Pope et al. (2016) we then subtract a background estimate chosen manually, for this larger set of light curves, we now choose the lowest 25% of pixels by median flux as being unlikely to be contaminated by stars, and take our background level to be the median of this at each time sample. To denoise this, we fit a Gaussian Process with a 30-day timescale squared exponential kernel using GEORGE (Ambikasaran et al. 2015), and our final background light curve is taken to be the posterior mean of this GP.

The dominant source of residual systematic errors in nominal *Kepler* time series is a common-mode variation primarily due to thermal changes on board the spacecraft, an issue which is traditionally dealt with by identifying and fitting a linear combination of systematic modes (Twicken et al. 2010; Stumpe et al. 2012; Smith et al. 2012; Petigura & Marcy 2012). We adopt the same approach here, using the *Kepler* Pre-search Data Conditioning (PDC) Cotrending Basis Vectors (CBVs) available from MAST, finding least-squares fits of either the first 4 or 8 CBVs to each light curve. We note that this can subtract astrophysical signals on long timescales, such that we use and recommend 4 CBV light curves for stars with variability on timescales longer than ~ 5 days, but otherwise use the 8 CBV light curves. There is some room for improvement here by simultaneously modelling astrophysical and instrumental variations, but this is beyond the scope of this paper. In the following, we will use the light curves with the lowest 6.5 hr Combined Differential Photometric Precision (CDPP) (Christiansen et al. 2012) out of all apertures, as calculated with the K2SC implementation (Aigrain et al. 2016). This is not necessarily the optimal choice for all red giants, especially those with oscillations on a 6.5 h timescale, but is a reasonable proxy nevertheless for white noise and leads to satisfactory results upon visual inspection of the present sample.

2.2 Asteroseismology

For all N red giants identified in this sample, we have attempted to extract the asteroseismic parameters $\nu_{\max}$ and $\langle\Delta\nu\rangle$ (Kjeldsen & Bedding 1995; Chaplin & Miglio 2013). These constrain fundamental stellar parameters independently from spectroscopic or interferometric measurements:

$$\nu_{\max} \propto \frac{g}{g_\odot} \cdot \frac{T_{\mathrm{eff}}}{T_{\mathrm{eff}\odot}}^{\frac{1}{2}} \tag{1}$$

and

$$\langle\Delta\nu\rangle \propto \sqrt{\langle\rho\rangle} = \sqrt{\frac{M}{\mathrm{M}_\odot}(\frac{R}{\mathrm{R}_\odot})^{-3}} \tag{2}$$

We follow the method of Davies & Miglio (2016), obtaining a Lomb-Scargle periodogram of the smoothed time series according to the method of García et al. (2011). We then conduct a Markov Chain Monte Carlo fit to this, applying the combined granulation and oscillation model of Kallinger et al. (2014), consisting of two Harvey profiles for the granulation (Harvey 1985), a Gaussian envelope for the stellar oscillations, and a white noise background for instrumental noise. We find that the marginal posterior distribution for the Gaussian envelope is well-approximated by a single Gaussian, and take its median and standard deviation to be our estimates for $\nu_{\max}$ and its uncertainty.

To estimate $\Delta\nu$, we divide the power spectrum through by the granulation and noise models to obtain a signal-to-noise spectrum, and fit a sum of Lorentzians separated by mean large ($\Delta\nu$) and small ($\delta\nu$) separations to the part of this spectrum in the vicinity of $\nu_{\max}$. In practice, for this dataset, $\delta\nu$ is poorly constrained, but mean $\langle\Delta\nu\rangle$ is typically well-constrained and its posterior marginal distribution is well-represented by a single Gaussian as with $\nu_{\max}$.

We obtain good estimates of these asteroseismic parameters for 35 targets, presented in Table 1. In many of the remainder of cases, we find that the very-low-frequency ($\lesssim 2\mu$Hz) oscillations are affected by filter artefacts from detrending, and we are not able to obtain good estimates for these stars.

Once $\nu_{\max}$ has been estimated, we use the asteroseismic scaling relation for $\nu_{\max}$ (Equation 1; Kjeldsen & Bedding 1995) to estimate $\log g$ in order to inform extraction of chemical abundances from spectra. Using the initial spectroscopic estimate of T_{eff}, which is not significantly informed by $\nu_{\max}$, we propagate uncertainties in $\nu_{\max}$ with Monte Carlo sampling.

For eight stars, we find that the asteroseismic fit is unsatisfactory: for BD+39 388 we cannot detect the expected oscillations; BD+43 3064 there are significant peaks but these are not consistent with the pattern expected from a red giant; for HD 179959 and HD 187217 we suspect contamination with the oscillations of a second giant, which is hard to remove from smear light curves; while for HD 188629, HD 188639 and HD 188875 we can extract a $\nu_{\max}$ but not a robust $\Delta\nu$. One star in our sample, the retired A star HD 185351, has a mode envelope that is not well fit by our model. The smear light curve for this star has already been published by Hjørringgaard et al. (2017), who showed with detailed asteroseismic modelling that it had a zero-age main sequence mass of $\sim 1.60\mathrm{M}_\odot$ and used it to calibrate the convective overshoot parameter for low-luminosity red giants. The bulk asteroseismic modelling presented here should therefore be considered to be superseded by the more detailed model of Hjørringgaard et al. (2017).

2.3 Spectroscopy

For the whole red giant sample, we have obtained high-resolution spectroscopy with TRES in order to constrain stellar parameters and elemental abundances. Operating with spectral resolving power $R = 44000$, we obtain signal-to-noise ratios of tens to hundreds per resolution element. We note that this resolution and SNR are sufficient for an exploratory study, but for more detailed analysis it will be desirable to use APOGEE or similar instruments at higher resolution and SNR. From this observing run we have 35 unique targets with seismic $\log g$ and spectra, one more star than the *Gaia*-ESO benchmark set and a significant addition to the ensemble of bright red giants with asteroseismic parameter determinations. These are unfortunately not the same 35 unique targets as for the asteroseismic analysis presented above in Section 2.2: due to observing constraints, we were unable to obtain spectra for BD+42 315, BD+48 290, HD 176209, HD 183354, HD 189636, or HD 189750.

Table 1. Bulk asteroseismic parameters $\Delta\nu$, ν_{max}, and ϵ for the red giant sample as discussed in Section 2.2.

Object	$\Delta\nu$ (μHz)	ν_{max} (μHz)	ϵ
BD+36 356	0.95 ± 0.03	5.08 ± 0.10	0.83 ± 0.20
BD+39 357	1.68 ± 0.01	13.27 ± 0.32	0.74 ± 0.06
BD+42 315	4.22 ± 0.03	38.32 ± 0.96	0.70 ± 0.07
BD+43 317	0.42 ± 0.05	1.98 ± 0.05	0.80 ± 0.17
BD+43 321	0.49 ± 0.01	2.56 ± 0.06	1.01 ± 0.07
BD+48 290	2.85 ± 0.01	23.13 ± 0.72	0.86 ± 0.08
BD+48 295	0.90 ± 0.01	5.44 ± 0.08	0.81 ± 0.05
HD 174020	0.56 ± 0.02	2.48 ± 0.10	0.89 ± 0.08
HD 174829	1.28 ± 0.01	7.95 ± 0.16	0.78 ± 0.06
HD 175740	5.93 ± 0.01	64.33 ± 0.78	1.00 ± 0.02
HD 175884	1.12 ± 0.01	7.07 ± 0.11	0.96 ± 0.08
HD 176209	4.22 ± 0.08	36.08 ± 0.77	0.87 ± 0.06
HD 178797	1.03 ± 0.02	6.34 ± 0.09	0.74 ± 0.29
HD 178910	3.64 ± 0.02	32.06 ± 0.31	0.83 ± 0.05
HD 179396	3.76 ± 0.02	31.02 ± 0.44	0.92 ± 0.03
HD 180312	4.17 ± 0.02	33.84 ± 0.28	0.96 ± 0.04
HD 180475	0.82 ± 0.00	4.34 ± 0.10	0.68 ± 0.03
HD 180658	4.00 ± 0.02	33.76 ± 0.50	0.90 ± 0.05
HD 180682	0.77 ± 0.05	3.68 ± 0.08	1.07 ± 0.15
HD 181022	0.38 ± 0.01	1.58 ± 0.03	0.70 ± 0.10
HD 181069	4.43 ± 0.01	41.46 ± 0.32	0.90 ± 0.02
HD 181097	1.61 ± 0.02	11.16 ± 0.14	0.72 ± 0.36
HD 181597	3.11 ± 0.01	25.84 ± 0.25	0.97 ± 0.02
HD 181778	2.56 ± 0.02	22.86 ± 0.29	0.72 ± 0.06
HD 181880	1.04 ± 0.01	6.54 ± 0.10	0.76 ± 0.05
HD 182531	1.03 ± 0.00	6.47 ± 0.09	0.86 ± 0.03
HD 182692	4.66 ± 0.01	44.38 ± 0.47	0.87 ± 0.02
HD 182694	5.71 ± 0.01	69.78 ± 1.02	0.94 ± 0.25
HD 183124	4.39 ± 0.01	39.59 ± 0.29	0.95 ± 0.03
HD 183354	2.66 ± 0.01	24.73 ± 0.37	0.74 ± 0.04
HD 185286	0.72 ± 0.01	4.23 ± 0.10	0.73 ± 0.08
HD 188537	1.55 ± 0.01	13.40 ± 0.34	0.72 ± 0.07
HD 189636	2.91 ± 0.01	25.97 ± 0.74	0.97 ± 0.04
HD 189750	4.16 ± 0.04	36.14 ± 0.58	0.94 ± 0.08
HD 226754	1.19 ± 0.01	7.41 ± 0.19	0.74 ± 0.08

To derive stellar parameters from our TRES spectra, we initially run the Stellar Parameter Classification (SPC: Buchhave et al. 2012) code to determine $T_{\rm eff}$ and $\log g$, using the SPC $T_{\rm eff}$ to inform the asteroseismic estimation of $\log g$ from ν_{max}. For deriving abundances, $T_{\rm eff}$ is fixed from the results of an initial SPC fit, while $\log g$ is fixed to the seismic values. The other stellar atmospheric parameters including the microturbulent velocity ($\nu_{\rm mic}$), and broadening (convolution by $V_{\rm mac}$, $\nu_{\sin i}$ and the instrumental line profile) as well as [Fe/H] and chemical abundances for 20 chemical species are derived using the Brussels Automatic Code for Characterizing High accUracy Spectra (BACCHUS: Masseron et al. 2016), and the results from this calculation are displayed in Table 2. BACCHUS uses an interpolation scheme through a grid of MARCS model atmospheres (Gustafsson et al. 2008) in combination with TURBOSPECTRUM (Alvarez & Plez 1998; Plez 2012). For the calculation of synthetic spectra, atomic line information has been taken from the fifth version of the Gaia-ESO linelist (Heiter et al., in preparation). Additionally we used the molecular species for CH (Masseron et al. 2014), CN, NH, OH, MgH C_2 (T. Masseron, private communication). The SiH molecular information is adopted from the Kurucz linelists and the information for TiO, ZrO, FeH, CaH from B. Plez (private communication).

Individual elemental abundances are derived by first fixing the stellar atmospheric parameters to those determined above. Spectra are then synthesized in regions centered around an absorption feature of the element we want to derive. The spectra generated will have different [X/Fe] values. A χ^2 minimization procedure is then done to derive the best fitting abundance for each line. The reported abundances are the median [X/Fe] value of the various line regions for a given element. To achieve the most precise abundances we have derived them using both with and without a line-by-line differential approach with respect to Arcturus (α Boötis) using the method described by Jofré et al. (2015) and the Arcturus abundances from (Hawkins et al. 2016c). The results of these absolute abundance calculations **without the line-by-line differential analysis implemented?**, are presented in Tables 3, 4 and 5. Because for most elements Arcturus differential abundances are not available, these are provided as supplementary online-only material. No abundances for oxygen could be reliably derived for any of the stars in our spectroscopic sample by either method.

3 RESULTS

3.1 Red Giants

3.2 Chemical Composition

place [X/Fe] vs [Fe/H] diagrams here and discuss which Galactic populations these stars come from. May also want to discuss how these span the typical Galactic populations and can act as benchmark stars for APOGEE or other large surveys

3.3 Other Stars

Ashley/Dan/Vichi?

4 OPEN SCIENCE

We believe in open science, and have therefore made all substantive products of this research available to the interested reader. All code used to produce smear light curves is available under a GPL v3 license at `github.com/benjaminpope/keplersmear`. All smear light curves, both including the red giant sample studied in detail in Section 3.1, and other stars as discussed in Section 3.2, can be downloaded from the Mikulski Archive for Space Telescopes (MAST) as a High-Level Science Product. TRES spectra are available from somewhere, and all asteroseismic parameters and derived stellar parameters for the red giants in Section 3.1 are provided in an online-only table as Supplementary Material to this paper.

All smear light curves in this paper, as well as the LaTeX source code used to produce this document, can be found at `github.com/benjaminpope/smearcampaign`.

5 CONCLUSIONS

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Table 2. Fundamental stellar parameters for the red giant sample as determined jointly by asteroseismology (asteroseismic log g; Section 2.2) and spectroscopy (RV, $T_{\rm eff}$, log g, [M/H], V sin i, and SNR; Section 2.3.)

Object	RV (km/s)	$T_{\rm eff}$ (K)	log g	[M/H]	V sin i (km/s)	SNR
BD+36 3564	−77.84 ± 0.05	4301 ± 50	2.06 ± 0.10	−0.34 ± 0.08	5.14 ± 0.50	71.8
BD+39 3577	−14.81 ± 0.07	5079 ± 50	3.00 ± 0.10	−0.11 ± 0.08	3.98 ± 0.50	92.8
BD+43 3064	−13.65 ± 0.06	4266 ± 50	2.03 ± 0.10	−0.21 ± 0.08	5.17 ± 0.50	69.2
BD+43 3171	−16.32 ± 0.11	4072 ± 50	2.02 ± 0.10	−0.17 ± 0.08	5.68 ± 0.50	68.6
BD+43 3213	−14.16 ± 0.16	4131 ± 50	2.07 ± 0.10	0.07 ± 0.08	6.24 ± 0.50	57.3
BD+48 2955	1.66 ± 0.04	4344 ± 50	2.11 ± 0.10	−0.32 ± 0.08	4.78 ± 0.50	31.7
HD 174020	−14.84 ± 0.08	4162 ± 50	1.97 ± 0.10	−0.10 ± 0.08	5.81 ± 0.50	120.1
HD 174829	10.15 ± 0.03	4482 ± 50	2.06 ± 0.10	−0.40 ± 0.08	4.41 ± 0.50	112.2
HD 175740	−8.82 ± 0.05	4973 ± 50	2.97 ± 0.10	−0.05 ± 0.08	3.66 ± 0.50	264.0
HD 175884	−34.39 ± 0.07	4466 ± 50	2.22 ± 0.10	−0.27 ± 0.08	4.46 ± 0.50	144.4
HD 178797	6.35 ± 0.05	4406 ± 50	2.21 ± 0.10	−0.37 ± 0.08	4.18 ± 0.50	77.1
HD 178910	−14.28 ± 0.05	4589 ± 50	2.46 ± 0.10	0.14 ± 0.08	4.26 ± 0.50	76.9
HD 179396	24.80 ± 0.04	4781 ± 50	2.51 ± 0.10	−0.21 ± 0.08	3.99 ± 0.50	82.7
HD 179959	−38.52 ± 0.09	4965 ± 50	2.19 ± 0.10	−0.23 ± 0.08	7.81 ± 0.50	129.3
HD 180312	−21.94 ± 0.05	4916 ± 50	2.55 ± 0.10	−0.44 ± 0.08	4.05 ± 0.50	73.5
HD 180475	−45.90 ± 0.08	4398 ± 50	2.15 ± 0.10	−0.44 ± 0.08	4.39 ± 0.50	58.4
HD 180658	2.97 ± 0.06	4802 ± 50	2.57 ± 0.10	−0.12 ± 0.08	3.81 ± 0.50	72.3
HD 180682	30.99 ± 0.07	4410 ± 50	2.14 ± 0.10	−0.51 ± 0.08	4.88 ± 0.50	80.1
HD 181022	−80.39 ± 0.16	4045 ± 50	2.06 ± 0.10	−0.28 ± 0.08	5.75 ± 0.50	108.8
HD 181069	9.99 ± 0.05	4842 ± 50	2.70 ± 0.10	−0.05 ± 0.08	3.53 ± 0.50	90.0
HD 181097	−5.60 ± 0.08	4520 ± 50	2.31 ± 0.10	−0.28 ± 0.08	4.08 ± 0.50	69.7
HD 181597	−13.06 ± 0.04	4751 ± 50	2.67 ± 0.10	−0.23 ± 0.08	2.23 ± 0.50	161.8
HD 181778	−22.04 ± 0.06	4664 ± 50	2.34 ± 0.10	−0.19 ± 0.08	4.23 ± 0.50	87.6
HD 181880	0.56 ± 0.08	4405 ± 50	2.23 ± 0.10	−0.30 ± 0.08	4.44 ± 0.50	71.2
HD 182531	−7.34 ± 0.05	4413 ± 50	2.24 ± 0.10	−0.24 ± 0.08	4.39 ± 0.50	71.4
HD 182692	−8.01 ± 0.05	4965 ± 50	3.06 ± 0.10	0.09 ± 0.08	3.40 ± 0.50	72.8
HD 182694	−0.87 ± 0.06	5178 ± 50	2.98 ± 0.10	−0.12 ± 0.08	5.12 ± 0.50	187.2
HD 183124	14.96 ± 0.01	4911 ± 50	2.85 ± 0.10	−0.15 ± 0.08	5.19 ± 0.50	114.3
HD 185286	−13.70 ± 0.08	4301 ± 50	2.08 ± 0.10	−0.14 ± 0.08	5.16 ± 0.50	135.6
HD 185351	−5.18 ± 0.04	5244 ± 50	3.66 ± 0.10	0.03 ± 0.08	2.02 ± 0.50	202.3
HD 187217	1.64 ± 0.05	4718 ± 50	2.41 ± 0.10	−0.17 ± 0.08	8.25 ± 0.50	59.9
HD 188537	−18.03 ± 0.15	4961 ± 50	2.41 ± 0.10	−0.08 ± 0.08	10.68 ± 0.50	67.0
HD 188629	10.97 ± 0.08	4227 ± 50	2.01 ± 0.10	−0.10 ± 0.08	5.53 ± 0.50	51.3
HD 188875	−13.71 ± 0.08	4473 ± 50	1.95 ± 0.10	−0.17 ± 0.08	7.07 ± 0.50	143.2
HD 226754	18.66 ± 0.10	4370 ± 50	2.36 ± 0.10	0.08 ± 0.08	4.78 ± 0.50	62.5

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Table 3. Chemical abundances relative to iron for stars in the red giant sample as determined by BACCHUS, without differential line-by-line comparison to Arcturus, as described in Section 2.3, for the elements Ca, Mg, Si, Ti, Al, Ba, and Na. Dashes indicate elements for which abundances could not be reliably computed.The catalogue of abundances for more elements continues in Tables 4 and 5.

Object	[Ca/Fe]	[Mg/Fe]	[Si/Fe]	[Ti/Fe]	[Al/Fe]	[Ba/Fe]	[Na/Fe]
BD+36 3564	0.21 ± 0.02	0.33 ± 0.03	0.10 ± 0.03	0.34 ± 0.04	0.40 ± 0.01	–	0.26 ± 0.08
BD+39 3577	0.13 ± 0.02	0.22 ± 0.04	-0.11 ± 0.02	0.08 ± 0.04	0.21 ± 0.01	0.35 ± 0.10	0.42 ± 0.00
BD+43 3064	0.19 ± 0.04	0.21 ± 0.03	-0.01 ± 0.03	0.28 ± 0.04	0.36 ± 0.01	–	0.48 ± 0.06
BD+43 3171	0.29 ± 0.03	0.26 ± 0.06	-0.00 ± 0.07	0.21 ± 0.06	0.42 ± 0.01	0.33 ± 0.18	0.18 ± 0.25
BD+43 3213	0.19 ± 0.03	0.23 ± 0.07	-0.18 ± 0.11	0.27 ± 0.07	0.37 ± 0.04	–	0.62 ± 0.37
BD+48 2955	0.22 ± 0.05	0.20 ± 0.03	0.08 ± 0.04	0.30 ± 0.04	0.30 ± 0.07	–	0.23 ± 0.14
HD 174020	0.33 ± 0.03	0.23 ± 0.04	-0.07 ± 0.06	0.29 ± 0.07	0.39 ± 0.03	–	0.26 ± 0.33
HD 174829	0.16 ± 0.04	0.20 ± 0.06	0.05 ± 0.05	0.19 ± 0.03	0.29 ± 0.01	–	0.31 ± 0.04
HD 175740	0.12 ± 0.02	0.07 ± 0.05	-0.05 ± 0.02	0.14 ± 0.03	0.21 ± 0.01	0.30 ± 0.07	0.34 ± 0.03
HD 175884	0.23 ± 0.02	0.20 ± 0.03	-0.01 ± 0.03	0.32 ± 0.03	0.34 ± 0.01	–	0.46 ± 0.06
HD 178797	0.22 ± 0.02	0.32 ± 0.03	0.06 ± 0.03	0.40 ± 0.04	0.42 ± 0.01	0.39 ± 0.22	0.45 ± 0.03
HD 178910	0.20 ± 0.03	0.20 ± 0.03	0.15 ± 0.05	0.20 ± 0.03	0.39 ± 0.04	0.25 ± 0.08	0.36 ± 0.98
HD 179396	0.09 ± 0.02	0.19 ± 0.03	0.04 ± 0.05	0.13 ± 0.02	0.27 ± 0.02	0.31 ± 0.03	0.28 ± 0.04
HD 179959	0.04 ± 0.04	0.06 ± 0.04	0.01 ± 0.03	0.03 ± 0.03	0.15 ± 0.02	–	0.38 ± 0.02
HD 180312	0.09 ± 0.02	0.21 ± 0.03	0.06 ± 0.03	0.09 ± 0.03	0.31 ± 0.01	0.37 ± 0.08	0.19 ± 0.01
HD 180475	0.23 ± 0.03	0.33 ± 0.03	0.03 ± 0.01	0.36 ± 0.04	0.41 ± 0.02	0.30 ± 0.20	0.40 ± 0.03
HD 180658	0.15 ± 0.03	0.19 ± 0.04	-0.01 ± 0.03	0.21 ± 0.03	0.35 ± 0.01	0.21 ± 0.09	0.39 ± 0.04
HD 180682	0.25 ± 0.02	0.45 ± 0.03	0.13 ± 0.02	0.47 ± 0.04	0.51 ± 0.05	0.19 ± 0.05	0.32 ± 0.01
HD 181022	0.34 ± 0.02	0.34 ± 0.06	0.01 ± 0.08	0.49 ± 0.06	–	0.31 ± 0.23	0.09 ± 0.48
HD 181069	0.13 ± 0.02	0.17 ± 0.04	-0.03 ± 0.05	0.19 ± 0.03	0.28 ± 0.02	0.26 ± 0.09	0.45 ± 0.06
HD 181097	0.25 ± 0.02	0.27 ± 0.03	-0.02 ± 0.03	0.35 ± 0.03	0.34 ± 0.02	–	0.46 ± 0.06
HD 181597	0.19 ± 0.02	0.20 ± 0.05	-0.03 ± 0.02	0.27 ± 0.04	0.28 ± 0.00	0.28 ± 0.05	0.42 ± 0.04
HD 181778	0.06 ± 0.03	0.12 ± 0.03	0.00 ± 0.03	0.09 ± 0.03	0.28 ± 0.02	0.47 ± 0.05	0.42 ± 0.12
HD 181880	0.26 ± 0.02	0.30 ± 0.03	0.06 ± 0.04	0.35 ± 0.03	0.42 ± 0.01	–	0.40 ± 0.05
HD 182531	0.22 ± 0.02	0.21 ± 0.05	-0.07 ± 0.03	0.37 ± 0.04	0.39 ± 0.01	–	0.48 ± 0.06
HD 182692	0.19 ± 0.03	0.18 ± 0.04	-0.12 ± 0.03	0.22 ± 0.04	0.35 ± 0.03	0.13 ± 0.05	0.38 ± 0.12
HD 182694	0.10 ± 0.02	0.11 ± 0.04	-0.04 ± 0.02	0.05 ± 0.02	0.14 ± 0.01	–	0.32 ± 0.01
HD 183124	0.17 ± 0.02	0.21 ± 0.04	-0.02 ± 0.04	0.19 ± 0.03	0.29 ± 0.00	0.25 ± 0.05	0.35 ± 0.02
HD 185286	0.34 ± 0.02	0.22 ± 0.04	-0.04 ± 0.04	0.40 ± 0.06	0.42 ± 0.02	–	0.55 ± 0.53
HD 185351	0.13 ± 0.03	0.08 ± 0.05	-0.08 ± 0.02	0.20 ± 0.03	0.22 ± 0.00	0.21 ± 0.09	0.38 ± 0.01
HD 187217	0.16 ± 0.04	0.28 ± 0.02	-0.09 ± 0.03	0.14 ± 0.04	0.32 ± 0.03	0.21 ± 0.14	–
HD 188537	0.11 ± 0.04	0.27 ± 0.04	0.02 ± 0.03	0.11 ± 0.04	0.25 ± 0.05	0.24 ± 0.07	–
HD 188629	0.30 ± 0.03	0.21 ± 0.03	-0.04 ± 0.07	0.37 ± 0.07	0.41 ± 0.04	–	0.46 ± 0.32
HD 188875	0.18 ± 0.04	0.22 ± 0.03	-0.07 ± 0.03	0.29 ± 0.04	0.33 ± 0.02	–	0.61 ± 1.09
HD 226754	0.30 ± 0.02	0.31 ± 0.04	0.03 ± 0.04	0.40 ± 0.06	0.48 ± 0.07	0.43 ± 0.00	0.47 ± 0.18

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Table 4. Chemical abundances relative to iron for stars in the red giant sample as determined by BACCHUS, without differential line-by-line comparison to Arcturus, as described in Section 2.3, for the elements Ni, Mn, Co, Eu, La, Zr, and Sr. Dashes indicate elements for which abundances could not be reliably computed.The catalogue of abundances for more elements continues in Table 5.

Object	[Ni/Fe]	[Mn/Fe]	[Co/Fe]	[Eu/Fe]	[La/Fe]	[Zr/Fe]	[Sr/Fe]
BD+36 3564	0.01 ± 0.04	0.08 ± 0.00	0.13 ± 0.02	0.25 ± 0.03	−0.02 ± 0.07	0.10 ± 0.02	0.34 ± 0.12
BD+39 3577	−0.05 ± 0.03	−0.03 ± 0.06	−0.02 ± 0.02	−0.22 ± 0.04	−0.25 ± 0.02	0.13 ± 0.08	–
BD+43 3064	0.05 ± 0.04	0.21 ± 0.02	0.13 ± 0.02	0.28 ± 0.06	0.15 ± 0.02	0.32 ± 0.04	0.25 ± 0.12
BD+43 3171	0.04 ± 0.05	0.11 ± 0.09	0.14 ± 0.05	0.21 ± 0.05	−0.06 ± 0.11	0.36 ± 0.07	–
BD+43 3213	0.06 ± 0.10	0.33 ± 0.07	0.03 ± 0.05	0.06 ± 0.04	−0.11 ± 0.05	0.49 ± 0.11	0.64 ± 0.47
BD+48 2955	0.05 ± 0.04	0.10 ± 0.02	0.12 ± 0.04	0.28 ± 0.04	0.24 ± 0.05	0.34 ± 0.05	–
HD 174020	0.05 ± 0.05	0.23 ± 0.02	0.10 ± 0.04	0.11 ± 0.04	0.02 ± 0.07	–	0.37 ± 0.89
HD 174829	−0.06 ± 0.04	−0.02 ± 0.07	0.05 ± 0.02	0.15 ± 0.01	0.12 ± 0.05	0.08 ± 0.03	–
HD 175740	0.03 ± 0.04	0.06 ± 0.01	0.08 ± 0.02	0.09 ± 0.07	0.12 ± 0.01	0.18 ± 0.02	–
HD 175884	0.04 ± 0.05	0.14 ± 0.02	0.10 ± 0.02	0.19 ± 0.02	0.14 ± 0.03	0.26 ± 0.02	–
HD 178797	0.05 ± 0.04	0.13 ± 0.11	0.18 ± 0.03	0.26 ± 0.02	0.14 ± 0.02	0.23 ± 0.03	–
HD 178910	0.28 ± 0.07	0.21 ± 0.05	0.17 ± 0.03	−0.02 ± 0.06	−0.13 ± 0.06	0.00 ± 0.03	–
HD 179396	−0.02 ± 0.04	0.09 ± 0.02	0.08 ± 0.03	−0.05 ± 0.03	0.05 ± 0.03	0.04 ± 0.02	–
HD 179959	−0.08 ± 0.04	−0.15 ± 0.04	−0.05 ± 0.02	0.16 ± 0.06	0.18 ± 0.01	0.14 ± 0.07	–
HD 180312	0.02 ± 0.03	−0.09 ± 0.03	0.07 ± 0.01	0.34 ± 0.05	0.04 ± 0.07	0.08 ± 0.02	–
HD 180475	0.03 ± 0.05	0.16 ± 0.04	0.19 ± 0.02	0.19 ± 0.07	0.18 ± 0.03	0.25 ± 0.03	–
HD 180658	0.03 ± 0.06	0.13 ± 0.03	0.11 ± 0.02	–	0.04 ± 0.04	0.16 ± 0.07	–
HD 180682	0.06 ± 0.04	−0.03 ± 0.08	0.20 ± 0.02	0.26 ± 0.03	−0.03 ± 0.02	0.22 ± 0.03	–
HD 181022	0.02 ± 0.07	0.05 ± 0.11	0.14 ± 0.05	0.26 ± 0.03	−0.03 ± 0.21	0.36 ± 0.14	–
HD 181069	0.08 ± 0.05	0.16 ± 0.03	0.12 ± 0.02	0.09 ± 0.03	0.02 ± 0.04	0.10 ± 0.03	–
HD 181097	0.01 ± 0.04	0.02 ± 0.11	0.14 ± 0.03	0.28 ± 0.04	0.17 ± 0.02	0.23 ± 0.03	–
HD 181597	0.03 ± 0.04	0.14 ± 0.01	0.13 ± 0.02	0.18 ± 0.03	0.13 ± 0.01	0.26 ± 0.03	–
HD 181778	−0.00 ± 0.05	0.13 ± 0.02	0.04 ± 0.02	0.16 ± 0.01	0.08 ± 0.03	0.11 ± 0.03	–
HD 181880	0.04 ± 0.04	0.10 ± 0.01	0.18 ± 0.03	0.32 ± 0.04	0.17 ± 0.02	0.33 ± 0.04	–
HD 182531	0.06 ± 0.04	0.17 ± 0.06	0.11 ± 0.02	0.16 ± 0.05	0.15 ± 0.03	0.36 ± 0.03	0.35 ± 0.14
HD 182692	0.03 ± 0.05	0.22 ± 0.02	0.15 ± 0.02	0.01 ± 0.05	0.06 ± 0.04	0.21 ± 0.03	–
HD 182694	−0.07 ± 0.04	−0.08 ± 0.02	0.03 ± 0.03	0.16 ± 0.02	0.16 ± 0.02	0.16 ± 0.04	–
HD 183124	−0.00 ± 0.05	0.01 ± 0.04	0.11 ± 0.02	0.17 ± 0.05	0.04 ± 0.06	0.14 ± 0.04	–
HD 185286	0.12 ± 0.04	0.25 ± 0.01	0.13 ± 0.03	0.18 ± 0.03	0.12 ± 0.05	0.52 ± 0.05	0.30 ± 0.05
HD 185351	0.01 ± 0.04	0.11 ± 0.02	0.15 ± 0.03	−0.06 ± 0.06	0.13 ± 0.03	0.29 ± 0.04	–
HD 187217	−0.03 ± 0.06	−0.10 ± 0.10	−0.03 ± 0.02	–	−0.07 ± 0.03	0.22 ± 0.04	–
HD 188537	0.05 ± 0.07	0.10 ± 0.03	0.12 ± 0.04	0.20 ± 0.04	0.15 ± 0.10	0.30 ± 0.04	–
HD 188629	0.10 ± 0.06	0.22 ± 0.01	0.10 ± 0.02	0.15 ± 0.03	0.06 ± 0.07	0.43 ± 0.01	0.34 ± 0.22
HD 188875	−0.02 ± 0.05	0.23 ± 0.02	0.09 ± 0.03	0.19 ± 0.07	0.20 ± 0.05	0.30 ± 0.03	–
HD 226754	0.19 ± 0.05	0.33 ± 0.03	0.23 ± 0.03	0.28 ± 0.07	−0.05 ± 0.07	0.34 ± 0.04	0.26 ± 0.13

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Table 5. Chemical abundances relative to iron for stars in the red giant sample as determined by BACCHUS, without differential line-by-line comparison to Arcturus, as described in Section 2.3, for the elements Zn, Y, Cr, V, Cu, and Sc. Dashes indicate elements for which abundances could not be reliably computed.

Object	[Zn/Fe]	[Y/Fe]	[Cr/Fe]	[V/Fe]	[Cu/Fe]	[Sc/Fe]
BD+36 3564	−0.29 ± 0.20	−0.27 ± 0.02	0.23 ± 0.00	0.15 ± 0.03	−0.04 ± 0.06	0.17 ± 0.02
BD+39 3577	−0.24 ± 0.71	−0.40 ± 0.04	0.16 ± 0.10	0.01 ± 0.02	−0.21 ± 0.01	−0.12 ± 0.05
BD+43 3064	–	−0.14 ± 0.05	0.32 ± 0.01	0.24 ± 0.03	−0.16 ± 0.10	0.14 ± 0.02
BD+43 3171	−0.40 ± 0.05	−0.31 ± 0.03	0.29 ± 0.04	0.12 ± 0.06	0.02 ± 0.11	0.14 ± 0.03
BD+43 3213	–	−0.06 ± 0.09	0.39 ± 0.01	0.08 ± 0.09	−0.28 ± 0.11	0.18 ± 0.04
BD+48 2955	–	−0.15 ± 0.05	0.23 ± 0.04	0.20 ± 0.03	−0.05 ± 0.04	0.15 ± 0.03
HD 174020	−0.48 ± 1.11	−0.19 ± 0.06	0.41 ± 0.06	0.26 ± 0.03	−0.20 ± 0.11	0.18 ± 0.03
HD 174829	−0.12 ± 0.13	−0.25 ± 0.06	0.16 ± 0.02	0.01 ± 0.02	−0.23 ± 0.03	0.12 ± 0.03
HD 175740	−0.16 ± 0.16	−0.09 ± 0.07	0.13 ± 0.04	0.09 ± 0.02	−0.16 ± 0.04	0.08 ± 0.03
HD 175884	−0.15 ± 0.17	−0.21 ± 0.07	0.26 ± 0.04	0.21 ± 0.02	−0.10 ± 0.05	0.13 ± 0.02
HD 178797	–	−0.08 ± 0.05	0.26 ± 0.04	0.19 ± 0.02	−0.11 ± 0.04	0.23 ± 0.03
HD 178910	−0.29 ± 0.74	−0.18 ± 0.05	0.29 ± 0.01	0.17 ± 0.02	0.21 ± 0.14	0.14 ± 0.02
HD 179396	−0.07 ± 0.15	−0.27 ± 0.07	0.12 ± 0.03	0.03 ± 0.02	−0.16 ± 0.06	0.10 ± 0.03
HD 179959	0.05 ± 1.84	−0.08 ± 0.06	−0.00 ± 0.03	−0.11 ± 0.02	−0.29 ± 0.05	0.10 ± 0.05
HD 180312	−0.18 ± 0.01	−0.23 ± 0.05	−0.06 ± 0.06	−0.05 ± 0.02	−0.15 ± 0.04	0.15 ± 0.05
HD 180475	−0.09 ± 0.11	−0.25 ± 0.08	0.24 ± 0.04	0.20 ± 0.02	−0.00 ± 0.04	0.21 ± 0.03
HD 180658	0.16 ± 1.25	−0.20 ± 0.01	0.19 ± 0.04	0.15 ± 0.02	−0.05 ± 0.06	0.12 ± 0.03
HD 180682	−0.23 ± 0.14	−0.29 ± 0.04	0.23 ± 0.03	0.26 ± 0.02	−0.06 ± 0.04	0.27 ± 0.02
HD 181022	−0.27 ± 0.03	−0.23 ± 0.02	0.19 ± 0.08	0.10 ± 0.08	−0.01 ± 0.12	0.25 ± 0.04
HD 181069	−0.02 ± 0.19	−0.11 ± 0.08	0.22 ± 0.03	0.15 ± 0.02	−0.10 ± 0.05	0.13 ± 0.03
HD 181097	−0.08 ± 0.41	−0.21 ± 0.03	0.25 ± 0.02	0.19 ± 0.03	−0.12 ± 0.03	0.22 ± 0.03
HD 181597	−0.14 ± 0.15	−0.19 ± 0.08	0.19 ± 0.05	0.21 ± 0.02	−0.18 ± 0.04	0.16 ± 0.02
HD 181778	−0.03 ± 0.18	−0.13 ± 0.04	0.18 ± 0.02	−0.02 ± 0.02	−0.25 ± 0.07	0.05 ± 0.02
HD 181880	−0.04 ± 0.22	−0.20 ± 0.07	0.27 ± 0.03	0.22 ± 0.02	−0.07 ± 0.03	0.23 ± 0.03
HD 182531	0.03 ± 0.78	−0.19 ± 0.07	0.29 ± 0.05	0.24 ± 0.03	−0.08 ± 0.05	0.18 ± 0.02
HD 182692	−0.24 ± 1.34	−0.21 ± 0.10	0.15 ± 0.07	0.24 ± 0.02	−0.11 ± 0.06	0.18 ± 0.03
HD 182694	−0.24 ± 0.07	−0.12 ± 0.05	0.04 ± 0.03	−0.05 ± 0.02	−0.26 ± 0.04	0.09 ± 0.05
HD 183124	−0.18 ± 0.17	−0.24 ± 0.03	0.12 ± 0.04	0.10 ± 0.02	−0.22 ± 0.02	0.10 ± 0.03
HD 185286	–	−0.19 ± 0.08	0.46 ± 0.01	0.34 ± 0.02	−0.11 ± 0.10	0.27 ± 0.03
HD 185351	−0.31 ± 0.10	−0.16 ± 0.05	0.16 ± 0.04	0.18 ± 0.02	−0.17 ± 0.03	0.12 ± 0.04
HD 187217	–	−0.37 ± 0.05	0.28 ± 0.03	0.11 ± 0.03	−0.23 ± 0.02	0.04 ± 0.05
HD 188537	0.32 ± 0.78	−0.27 ± 0.09	0.17 ± 0.01	0.11 ± 0.02	−0.17 ± 0.04	0.06 ± 0.05
HD 188629	–	−0.04 ± 0.10	0.30 ± 0.06	0.31 ± 0.04	−0.15 ± 0.09	0.22 ± 0.04
HD 188875	0.31 ± 1.71	−0.04 ± 0.07	0.33 ± 0.07	0.18 ± 0.02	−0.25 ± 0.07	0.13 ± 0.03
HD 226754	−0.22 ± 1.07	−0.33 ± 0.04	0.38 ± 0.07	0.45 ± 0.04	−0.02 ± 0.07	0.30 ± 0.04