Astronomy & Astrophysics manuscript no. master
April 28, 2017

High resolution near-IR spectroscopy of Arcturus and 10 Leo

Refining a near-IR iron line list

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Received ...; accepted ...

ABSTRACT

Context. Reliable stellar atmospheric parameters for FGK stars have been **commonly** obtained from methods that rely on high resolution and high signal-to-noise optical spectroscopy. The advent of a new generation of high resolution near-IR spectrographs opens the possibility of using classic spectroscopic methods with high resolution and high signal-to-noise in the NIR spectral window.
Aims. We aim to obtain precise and accurate atmospheric stellar parameters using high quality spectra of two K giant stars, Arcturus and 10 Leo.
Methods. Our spectroscopic analysis is based on the iron excitation and ionization balance done in LTE and a line list of Fe I and Fe II lines in the NIR domain. The line list is being refined from our previous study, allowing us to obtain more reliable parameters.
Results. We successfully obtain atmospheric parameters for two K giants in agreement with average literature values adopted.
Conclusions. With these results we are now extending the line list towards cooler stars, thus allowing us to explore the M dwarf stars in the future, known to form Earth-like planets.

Key words. data reduction: high resolution spectra – stars individual: Arcturus – stars individual: 10 Leo

1. Introduction

Effective temperature (T_{eff}), surface gravity ($\log g$), and metallicity ([M/H], where iron is normally used as a proxy) are fundamental atmospheric parameters necessary to characterise a single star, and to indirectly determine other fundamental parameters such as mass, radius, and age from stellar evolution models (see e.g. Girardi et al. 2000; Dotter et al. 2008; Baraffe et al. 2015). Precise and accurate stellar parameters are also essential in exoplanet searches. Planetary radius and mass are mainly found from transit lightcurve analysis and radial velocity analysis, respectively. The determination of the mass of the planet implies a knowledge of the stellar mass, while the measurement of the radius of the planet is dependent on our capability to derive the radius of the star (see e.g. Torres et al. 2008; Ammler-von Eiff et al. 2009; Torres et al. 2012).

The derivation of precise stellar atmospheric parameters is not a simple task. Different approaches often lead to discrepant results (see e.g. Torres et al. 2010; Lebzelter et al. 2012a; Santos et al. 2013). Interferometry is usually considered an accurate method for deriving stellar radii (see e.g. Boyajian et al. 2012); however, it is only applicable for bright nearby stars. Asteroseismology, on the other hand, reveals the inner stellar structure by observing the stellar pulsations at the surface. From asteroseismology it is possible to measure the surface gravity and mean density, and therefore to calculate mass and radius with high precision (see e.g. Kjeldsen & Bedding 1995). However, for stars on the main sequence asteroseismic methods can typically only be applied to FG stars, since the oscillation modes of K and M dwarfs are likely too weak to be detected even with high precision spectroscopy or photometry. Moreover, the effective temperature is needed when applying asteroseismology in order to obtain the surface gravity and the mean density.

A crucial parameter for the indirect determination of stellar bulk properties is T_{eff}. In that respect, the infrared flux method (IRFM) has proven to be reliable for FGK dwarf and subgiant stars. For higher accuracy the IRFM needs a priori knowledge of the bolometric flux, reddening, surface gravity, and stellar metallicity (Blackwell & Shallis 1977; Ramírez & Meléndez 2005; Casagrande et al. 2010).

Finally, the use of high resolution spectroscopy along with stellar atmospheric models is an extensively tested method that allows the derivation of the fundamental parameters of a star (see e.g. Valenti & Fischer 2005; Santos et al. 2013). **The procedure depends on the quality of the spectra, their resolution, wavelength region, and the set of software used. The latter includes the atmosphere models, radiative transfer code, and atomic data used.** A fit to the overall spectrum can be applied for all spectral resolutions, but is often time consuming (see e.g. Recio-Blanco et al. 2006; Tsantaki et al. 2014). For resolutions larger than $\lambda/\Delta\lambda > 20\,000$ we can apply the equivalent width (EW) method (see e.g. Tsantaki et al. 2013; Andreasen et al. 2017, for details). However, while the latter approach is often faster than the synthetic fitting, it requires high quality spectra, and the star to be a slow rotator (below 10 km/s to 15 km/s). **It also fails for cool stars due to severe continuum depression.**

Standard procedures are often used to derive stellar atmospheric parameters from high quality spectra in the optical (see e.g. Valenti & Fischer 2005; Sousa et al. 2008). With the advancement of high resolution near-infrared (NIR) instruments, we will now be able to use a similar technique to that used in the optical part of the spectrum (see e.g. Meléndez & Barbuy 1999; Sousa et al. 2008; Tsantaki et al. 2013; Mucciarelli et al. 2013; Bensby et al. 2014). Such an effort seems very timely because of the growing number of observing facilities offering a high-resolution access to the near infrared range. At the moment, the GIANO spectrograph installed at *Telescopio Nazionale Galileo* (TNG) is already available (Origlia et al. 2014), as is the *infrared Doppler instrument* (IRD) installed at the Subaru telescope (Kotani et al. 2014), *Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs* (CARMENES) for the 3.5 m telescope at Calar Alto Observatory (Quirrenbach et al. 2014), iShell at the *InfraRed Telescope Facility* (Rayner et al. 2012, 2016), **and *The Apache Point Observatory Galactic Evolution Experiment* (APOGEE) (Allende Prieto et al. 2008)**. Three new spectrographs are planned for the near future: 1) The *CRyogenic InfraRed Echelle Spectrograph Upgrade Project* (CRIRES+) at the *Very Large Telescope* (VLT) (Follert et al. 2014) with expected first light in 2017, 2) *un SpectroPolarimètre Infra-Rouge A Near-InfraRed Spectropolarimeter* (SPIRou) at *The Canada-France-Hawaii Telescope* (CFHT) (Delfosse et al. 2013; Artigau et al. 2014) with expected first light in 2017 as well, and 3) *Near Infrared Planet Searcher* NIRPS at the ESO 3.6m telescope in La Silla (Conod et al. 2016). The spectral resolutions for these spectrographs range between 50 000 and 100 000.

With the advance of the next generation NIR spectrographs, we are still preparing the data analysis of stellar spectra, in particular how to get reliable atmospheric parameters (see e.g. Önehag et al. 2012; Lindgren et al. 2016; Andreasen et al. 2016). The analysis of stellar spectra is well understood for FGK stars in the optical part of the spectrum, however some work still needs to be done for the NIR part.

We continue our series of studies to explore the use of the NIR domain to derive stellar parameters for FGK and M stars. Here we analyse the atlas of Arcturus and the spectrum of 10 Leo. For the analysis we use the iron line list presented in Andreasen et al. (2016) (referred to as Paper I). In Paper I we successfully tested our method on a slightly hotter star than the Sun, while in this work we aim to test the method on cooler stars. The strength of the NIR domain over the optical becomes clear when we move towards the cooler stars. Here we see less continuum depression and line blending due to in particular molecular features. Moreover, the cooler stars emit more light in the NIR domain than the optical, and with the stars with the lowest masses being intrinsically faint, we thus obtain the majority of the flux here.

2. Data

2.1. The stars

While the community is currently on the verge to access large amounts of high resolution NIR spectra, the available spectra at the moment are sparse. We chose to use two stars cooler than the Sun since we used a star hotter than the Sun (HD 20010) in Paper I. **We will however use all four stars in this work for various reasons. The solar spectrum will be used for inspecting the line list presented in Paper I. This spectrum was obtained from the Kitt Peak telescope by Hinkle et al. (1995b). The spectrum of HD 20010 will be reused from Paper I as well. This spectrum was obtained by the CRIRES spectrograph by Lebzelter et al. (2012b) as part of the CRIRES-POP. HD 20010 will be reanalysed as to confirm the improvement of the refined line list which will be presented in the section below. The two stars which we have not analysed before are Arcturus and 10 Leo.**

The atlas of Arcturus (acquired at Kitt Peak National Observatory using the FTS spectrograph at the Mayall telescope), one of the brightest stars on the Northern hemisphere. Thus it is well studied (see e.g. Griffin & Griffin 1967; McWilliam 1990; Ramírez et al. 2013, to mention just a few) **and a benchmark star in current spectroscopic surveys such as GAIA-ESO ()**. We use the atlas from Hinkle et al. (1995a) which covers the spectral range of interest (YJHK bands). Strong telluric features were identified with a spectrum from the TAPAS web page (Bertaux et al. 2014). The atlas also comes with a telluric standard and the ratio of the two spectra in order to correct for the tellurics. The telluric spectrum from TAPAS is only used for telluric line identification. We use both the telluric corrected and non-corrected spectrum.

The spectrum for 10 Leo is from the CRIRES-POP team (Nicholls et al. 2017). 10 Leo is very similar to Arcturus, which is also one reason this star was the first to be fully reduced by the CRIRES-POP team. The spectrum is divided into several pieces according to the atmospheric windows in the NIR: YJ (only together), H, K, L, and M. We use only the first three. Some small gaps are present in the spectrum due to tellurics that could not be properly removed, low S/N, bad pixels, etc. Rather than giving an uncertain interpolation, Nicholls et al. (2017) decided to leave small gaps in the data. This has very little effect on our line by line analysis. However, we were unable to measure one Fe II line due to the gaps which are generally important to determine the surface gravity.

The data for the two stars are very similar in terms of S/N (around 300 as measured by IRAF in a continuum region in the YJ band), resolution (approximately 100 000), and spectral coverage. In Fig. 1 we compare the spectra of the two stars in a region with some of the iron lines used for the analysis described below. **The two stars have very similar spectral type as seen from the two spectra. The difference is shown in the bottom of the figure in red.**

A summary of the four stars used can be seen in Table 1. The parameters are obtained from the PASTEL catalogue (Soubiran et al. 2016) which is a compilation of stellar atmospheric parameters from the literature obtained mostly from high resolution and high S/N spectra. The parameters are the median values of all measurements for a given star, where the errors reported are the standard deviation of this. ξ_{micro} is estimated using the empirical relation by Tsantaki et al. (2013) for dwarf stars, i.e. $\log g \geq 3.95$, and Adibekyan et al. (2015) for the rest. This is done for each literature value in the catalogue. The value presented in the Table here is calculated on the same way as the rest of the parameters.

2.2. The line list

There have been different recent studies compiling line lists for high resolution NIR spectra. For M dwarfs there is the line list by Önehag et al. (2012); Lindgren et al. (2016), which has been tested extensively on CRIRES spectra. For FGKM giants there is the line list used by the APOGEE team compiled by Shetrone et al. (2015).

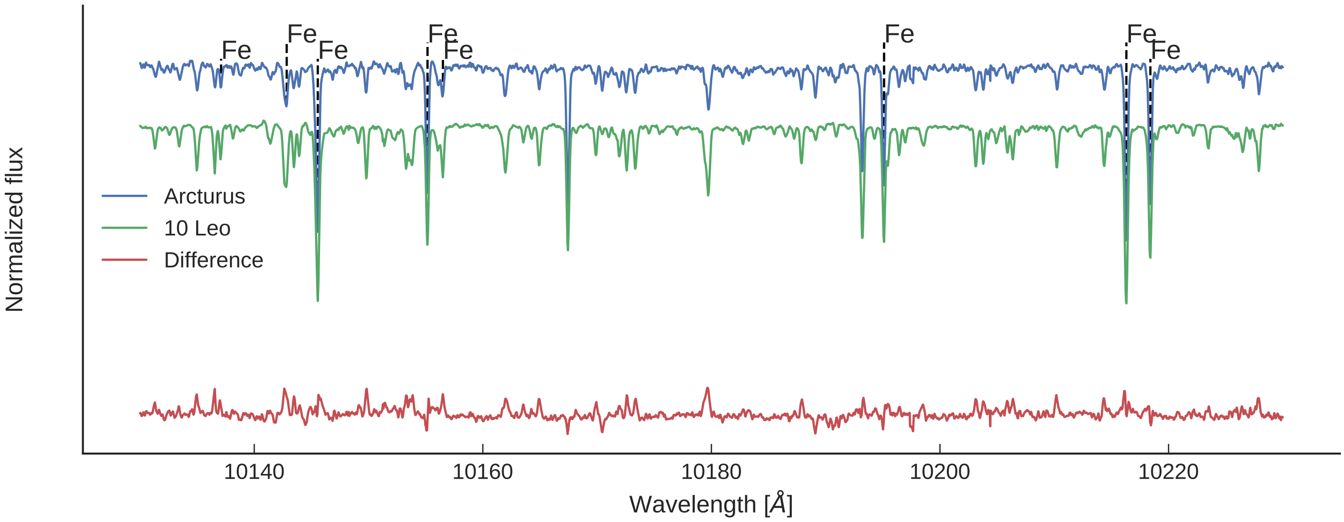

Fig. 1. Sample spectra of the two stars, in blue is Arcturus, and green is 10 Leo with an offset. We mark the location of Fe I lines in the region. **The red curve in the bottom is the difference in flux between the two stars, indicating they are very similar.**

Table 1. Summary of the four stars used in this work. The stellar parameters are from the PASTEL catalogue (Soubiran et al. 2016) (see text for details), except the parameters for the Sun.

Star	Spectrographs	Resolution	$T_{\rm eff}$ (K)	$\log g$ (dex)	$\xi_{\rm micro}$ (km/s)	[Fe/H] (dex)
Sun	FTS	600 000	5777	4.44	1.00	0.00
Arcturus	FTS	100 000	4300 ± 111	1.60 ± 0.29	1.93 ± 0.17	-0.54 ± 0.11
HD 20010	CRIRES	100 000	6152 ± 95	3.96 ± 0.11	1.17 ± 0.24	-0.27 ± 0.06
10 Leo	CRIRES	100 000	4742 ± 61	2.76 ± 0.17	1.45 ± 0.08	-0.03 ± 0.02

Since we wanted to compile a line list for FGK, and possible M dwarf stars, we decided to start from the VALD3 database (Piskunov et al. 1995; Kupka et al. 2000). This has not been done for the NIR previously. In Paper I we prepared a Fe I and Fe II line list in the NIR domain. **The atomic data from the lines were in a wavelength region ranging from** (10 000 **to** 25 000) Å**, covering the YJHK bands. EWs were measured for all iron lines with ARES (Sousa et al. 2015), discarding any line with EW below** 5 mÅ **or above** 200 mÅ**. The oscillator strengths of the line list was calibrated using the solar spectrum, and the solar iron abundance from Gonzalez & Laws (2000) at 7.47. This was done using the radiative transfer code MOOG (Sneden 1973) for obtaining the abundances of individual iron lines and an atmosphere model provided by Kurucz (1993).** The line list was successfully used to derive atmospheric parameters for a late F star, **HD20010**.

3. Refining the NIR line list

In this work we will go one step forward, and test this line list for **two** K type stars. **Before** testing the line list from Paper I at cooler effective temperatures with two K stars, it is a primary goal of this work to refine the line list. This includes identifying recurring outliers (both from the work done in Paper I and in this work), and lines which we are not able to measure, e.g. if a line is amidst a forest of telluric lines. **The refinement is needed, since we experienced some inconsistencies with especially the derived metallicity compared to literature values. While the metallicity for HD 20010 (the star analysed in Paper I) were within the errors with those from the literature, it was overestimated. The errors on all parameters were also quite high compared to what is achievable for similar quality spectra from the visible.** To identify these lines the solar atlas used in Paper I was revisited. In total 211 out of 295 Fe I lines and 8 out of 13 Fe II lines were removed in the process. Most of these were blended lines with either tellurics or other stellar lines. This procedure leaves us with 84 Fe I lines and 5 Fe II lines. These lines should be the best for deploying our technique of determining atmospheric stellar parameters.

During a second look at the Solar spectrum, the EW of the lines were measured by hand (this had previously been done automatically with ARES). Since we re-measured the EWs, the oscillator strengths, $\log gf$, had to be re-calibrated again. Here we simply change the $\log gf$ values for the measured EW until the abundance of a given line is equal to that of the Sun, using the same solar atmosphere model as in Paper I. The mean change in $\log gf$ for common lines is -0.09 ± 0.16. The line list with the updated $\log gf$ is presented in Appendix A.

The Fe II lines are used to determine $\log g$ by imposing ionization balance with the average Fe I abundance. However, the low number of Fe II lines available is a concern, since the average abundance of Fe II is affected more by small number statistics compared to the numerous Fe I lines.

4. Obtaining stellar parameters

The method used both in Paper I and here is based on the determination of the iron abundances on a number of lines from their measured EWs. This is done using the radiative transfer code MOOG (Sneden 1973) is used to determine the iron abundance from the measured EWs. Then ionization

balance between Fe I and Fe II lines, and excitation balance for all Fe I lines is imposed, by changing the atmospheric parameters for the model atmosphere (Kurucz 1993, is used here). While this is a well tested method for getting atmospheric parameters utilising the optical part of the spectrum, it is a novel approach in the NIR. Due to its novelty, the measurements of EWs are done with both hand (IRAF) and manually (ARES) as a quality check. For both the automatically and manually measured EWs, we discard all lines with an EW below 5 mÅ and above 150 mÅ before continuing the analysis. Lines outside this range are either too weak to be reliably measured or saturated and does no longer contain information about the abundance. The entire procedure of obtaining the stellar parameters is done with the software FASMA (Andreasen et al. 2017) which does the minimization when imposing ionization end excitation balance.

5. Results

The results for the revisited spectrum of HD 20010, and the two additional K stars are presented here.

5.1. Revisiting HD 20010

As a first step we revisit HD 20010 for which we derived atmospheric stellar parameters in Paper I using the newly revised line list presented in this paper. The results are shown in Table 2 along with the average literature values (see Paper I and references therein). We see better agreement with the average literature values adopted (especially [Fe/H] and $\log g$), and smaller errors with the updated results. This suggests that the new line list is more reliable.

5.2. Arcturus

Arcturus is one of the brightest stars on the night sky with a V magnitude of -0.05 (Ducati 2002). Hence it is a prime target for testing with the numerous measurements of the atmospheric parameters as mentioned above.

The atlas consists of both a summer observation set and a winter observation set. The two data sets have been obtained in order to minimise the effect of tellurics at different spectral regions. A comparison between the two sets of measured EWs - both the manual measurements using IRAF and the automatic measurements using ARES - are shown in Fig. 2. The automatic EW measurements for the summer set and winter set show excellent agreement. This means that the two data sets are very similar, thus we decided to only manually measure the EWs for one set (summer). We did, however, measure a few lines from the winter data set to verify the agreement. For all three sets of measured EWs (summer and winter observations automatically, and summer manually), parameters were derived with and without $\log g$ set to a fixed value (1.69 dex, the average literature value adopted). The derivation of the parameters followed the procedure presented in Paper I, although we used the minimization routine from Andreasen et al. (2017). After we reached convergence using all the iron lines we were able to measure, one outlier above 3σ in abundance were removed, and the minimization routine was restarted. This process was done iteratively until there were no more outliers. The final results are presented in Table 3 together with mean parameters from the literature.

We generally see good agreement between the derived parameters and the average values from the literature adopted. The

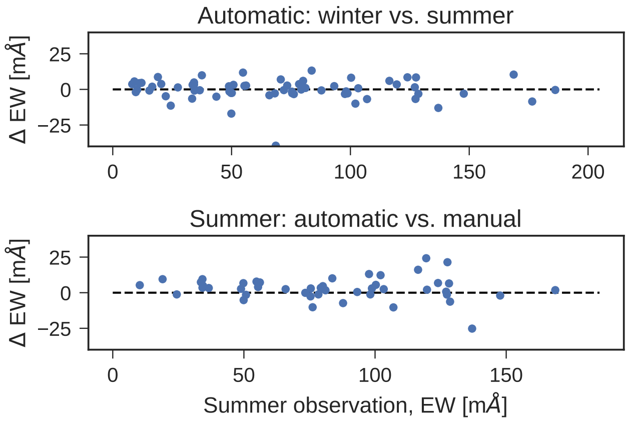

Fig. 2. Top figure: Difference of the automatic EW measurements between the summer observations and winter observations from the Arcturus spectra. Bottom figure: Same as above, but with manual measurements from ARES (summer) and automatic measurements (summer).

only parameter being difficult to measure is the surface gravity due to the low number of Fe II lines in the NIR. It is very important to derive the metallicity accurately, and we report consistent results overall, especially with the automatic measurements, compared to literature values. When measuring the EWs by hand, we might have systematically overestimated the continuum, resulting in higher [Fe/H]. For visualisation the parameters are plotted (except ξ_{micro}) in Fig. 3. Here the histogram shows the literature values collected from Simbad while the vertical black line is our final value with grey shaded errorbar. The plot shows that our values are in very good agreement with the literature results, supporting the quality and reliability of our analysis.

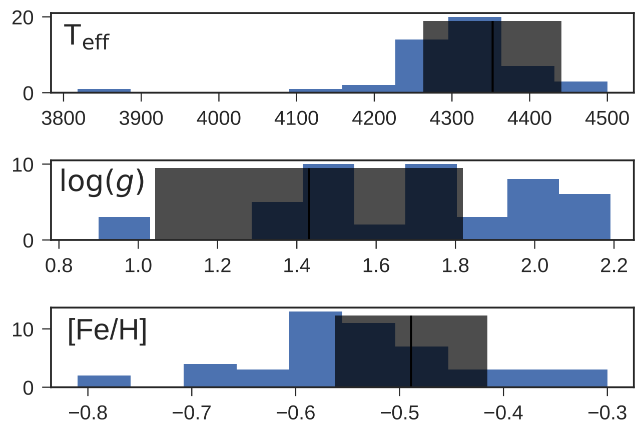

Fig. 3. Histogram of the different sets of literature parameters of Arcturus (except ξ_{micro}). The black vertical line are our derived parameters, and the grey shaded area are the errors on the corresponding parameters.

5.3. 10 Leo

The approach for determining the atmospheric stellar parameters for 10 Leo is identical to Arcturus. We use ARES on each band (YJ, H, and K-band) separately. For the small gaps in the spectrum, we simply set the flux to 1, since the spectrum is already

Table 2. Updated results for HD 20010 using the shorter line list and new $\log gf$.

	$T_{\rm eff}$ (K)	$\log g$ (dex)	$\xi_{\rm micro}$ (km/s)	[Fe/H] (dex)
Literature	6131 ± 255	4.01 ± 0.60	1.90 ± 1.08	−0.23 ± 0.14
This work	6157 ± 180	4.06 ± 0.76	1.62 ± 0.44	−0.18 ± 0.11
This work	6153 ± 176	4.01 (fixed)	1.68 ± 0.40	−0.18 ± 0.11
Paper I	6116 ± 224	4.21 ± 0.58	2.45 ± 0.45	−0.14 ± 0.14
Paper I	6144 ± 212	4.01 (fixed)	2.66 ± 0.42	−0.13 ± 0.29

Table 3. The derived parameters for Arcturus with and without fixed surface gravity.

	$T_{\rm eff}$ (K)	$\log g$ (dex)	$\xi_{\rm micro}$ (km/s)	[Fe/H] (dex)
Literature	4306 ± 100	1.69 ± 0.32	1.92 ± 0.15	−0.54 ± 0.11
IRAF (summer)	4380 ± 79	0.64 ± 0.33	1.14 ± 0.09	−0.49 ± 0.07
IRAF (summer)	4212 ± 77	1.69 (fixed)	1.25 ± 0.08	−0.37 ± 0.03
ARES (summer)	4439 ± 63	1.20 ± 0.20	1.55 ± 0.10	−0.58 ± 0.06
ARES (summer)	4348 ± 75	1.69 (fixed)	1.58 ± 0.09	−0.53 ± 0.03
ARES (winter)	4436 ± 67	0.55 ± 1.77	1.35 ± 0.09	−0.56 ± 0.07
ARES (winter)	4233 ± 109	1.69 (fixed)	1.43 ± 0.09	−0.49 ± 0.04
Weighted mean	4421 ± 40	0.96 ± 0.60	1.34 ± 0.05	−0.55 ± 0.04
Weighted mean	4269 ± 51	1.69 (fixed)	1.41 ± 0.05	−0.46 ± 0.02

normalised. This will also prevent ARES to identify and measure any lines in these regions. The EWs from the three regions are combined to one final line list used for the determination of the parameters. The EWs were also measured by hand using IRAF. We list the results in Table 4 alongside with an average of literature values taken from Simbad. The final results and five collected literature values are presented in Fig. 4.

Generally the derived parameters are in excellent agreement with the literature values listed here. We were able to derive good $\log g$ values, although with larger errors compared to the results from the literature.

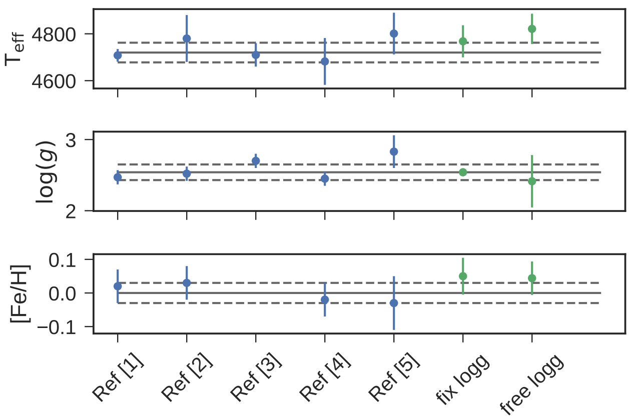

Fig. 4. Literature values (blue) and the two results from this work (green) with and without $\log g$ fixed. The errorbars on the literature values are either those presented in the corresponding paper, or in the cases none were presented we give an error of 100 K for $T_{\rm eff}$, 0.10 dex for $\log g$, and 0.05 dex for [Fe/H]. The horizontal lines are the average literature values adopted. References: Ref [1]: Luck (2015), Ref [2]: Park et al. (2013), Ref [3]: Massarotti et al. (2008), Ref [4]: Soubiran et al. (2008), and Ref [5]: da Silva et al. (2011).

6. Discussion

6.1. The role of $\log g$

One of the most difficult atmospheric stellar parameters to get from a spectrum is the surface gravity. For this we need the lines of pressure sensitive ionized atoms such as Fe II. However, they are more sparse than neutral iron, Fe I, making the determination more challenging. This is true in the optical (see e.g. the discussion by Mortier et al. 2013), and even more in the NIR (see e.g. Paper I). One solution to this problem is to fix the value of surface gravity and derive the other parameters. With the parallaxes from e.g. Gaia (Gaia Collaboration et al. 2016) we will have access to accurate $\log g$. However, this requires a priori knowledge of the mass from e.g. isochrones, and $T_{\rm eff}$. By iteratively obtaining the $T_{\rm eff}$ from spectroscopy and the corresponding $\log g$ from the parallaxes, we can obtain reliable $T_{\rm eff}$, $\log g$, and [Fe/H]. **Another approach is to use asteroseismic $\log g$ which are becoming a new standard. This has previously been done in the APOGEE+*Kepler* (APOKASC) context by Pinsonneault et al. (2014); Hawkins et al. (2016). It is important to mention, that the asteroseismic $\log g$ in turn is dependent on $T_{\rm eff}$ through the scaling relations (see e.g. Kjeldsen & Bedding 1995).**

As seen from Fig. 3, the distribution of $\log g$ values from the literature are rather disperse. Since there is a dependence between the other derived parameters with $\log g$, simply using a mean value as a reference value can lead to misleading parameters. To verify the impact of using the wrong $\log g$ as baseline, we tested what was the $T_{\rm eff}$ and [Fe/H] that we derive by setting $\log g$ fixed to values between 0.9 dex and 2.2 dex, i.e., in the range of the literature values found. The results show that $T_{\rm eff}$ and [Fe/H] can change by 200 K and 0.21 dex, respectively. This is most likely the origin of the small discrepancies seen for the parameters of Arcturus when the $\log g$ is fixed and free.

Note that the ionized iron lines are not only sparse, they are also rather weak. The lowest measured EW for an Fe II line is 7.8 mÅ (in Arcturus), while the highest measured value is 20.7 mÅ (in 10 Leo). However, with the upcoming high quality spectra for the NIR, the community should still be able to measure these Fe II lines. We showed in Paper I that a minimum

Table 4. Results from 10 Leo presented in the same way as for Table 3.

	$T_{\rm eff}$ (K)	$\log g$ (dex)	$\xi_{\rm micro}$ (km/s)	[Fe/H] (dex)
Literature	4720 ± 42	2.54 ± 0.11	1.59 ± 0.02	0.00 ± 0.03
IRAF	4835 ± 85	2.41 ± 0.41	1.28 ± 0.08	0.09 ± 0.06
IRAF	4768 ± 88	2.54 (fixed)	1.20 ± 0.08	0.01 ± 0.05
ARES	4805 ± 98	2.42 ± 0.61	1.23 ± 0.10	−0.01 ± 0.07
ARES	4768 ± 105	2.54 (fixed)	1.20 ± 0.10	−0.01 ± 0.06
Weighted mean	4821 ± 65	2.41 ± 0.37	1.26 ± 0.06	0.04 ± 0.05
Weighted mean	4768 ± 69	2.54 (fixed)	1.20 ± 0.06	0.05 ± 0.04

S/N of around 50 is required to utilise this method, however this was only tested for the Sun, and a higher S/N might be needed for other spectral types.

6.2. Proper data reduction

The relative novelty of NIR high resolution spectroscopy is reflected on a number of problems regarding the available spectra that made our analysis particularly difficult. For instance, in Paper I we had to deal with a less reliable wavelength calibration for the spectrum of HD 20010. This meant the wavelength was stretched when compared to a synthetic spectrum, which is discussed in more detail by Nicholls et al. (2017). The poor wavelength calibration for HD 20010 most likely caused bad EW measurements. In addition, the spectrum was not corrected for telluric lines which also caused minor deviation from the true EW when measured. Another reason was the non-refined line list used, which we have attempted to correct for here. The refined line list has made the derivation of the metallicity more reliable compared with the adopted literature as it is demonstrated in Sec. 5.1. It is expected that even better results will be obtained for this star once the final spectrum is presented by the CRIRES-POP team.

All the above problems we had with HD 20010 have been solved for 10 Leo, and it is clear the results are of much higher quality. This can be seen by the smaller errors we have on our parameters, and the good agreement of all parameters compared with the literature. Therefore, it may be necessary that a telluric correction is applied to the spectrum before atmospheric stellar parameters can be determined reliably. However, with our limited sample it is difficult to make a clear conclusion yet. Note that this is unlike the optical where a telluric correction is not necessary for obtaining atmospheric parameters.

7. Conclusion

In this paper we presented a refined Fe I and Fe II line list in the NIR domain. The method should work in all spectral ranges, however, it is important to locate the appropriate iron lines. For the NIR we need a relative large coverage (YJHK, although few lines are in the K band). The method used here which is usually adopted in the optical domain to derive parameters is now available for the NIR as well. The refined line list has been used to derive new parameters for the late F-star HD 20010, as well as for two K-giants (Arcturus and 10 Leo). The results show that the stellar atmospheric parameters derived using our line list are perfectly compatible with the literature values. We are thus now extending the line list towards cooler temperatures. With the updated results for HD 20010, and the results for Arcturus and 10 Leo, we are now reaching the same precision that has been reached in the optical for similar spectral types using the same methodology. The obvious next step is to approach the even cooler M stars. Particular interesting are the M dwarf stars, known to be prone forming rocky planets. As important as cooler stars, we have yet to test our line list on any dwarf stars other than the Sun for which our line list is calibrated. The upcoming spectral library from CARMENES (priv. comm. with P. Amado) will provide the community with high quality spectra and allow us to extend our test to many different spectral types of interest.

Acknowledgements. We thank José Caballero for many useful comments during the process which led to this paper. This work was supported by Fundação para a Ciência e a Tecnologia, FCT, (ref. UID/FIS/04434/2013, PTDC/FIS-AST/1526/2014, and PTDC/FIS-AST/7073/2014) through national funds and by FEDER through COMPETE2020 (ref. POCI-01-0145-FEDER-007672, POCI-01-0145-FEDER-016886, and POCI-01-0145-FEDER-016880). N.C.S., and S.G.S. acknowledge the support from FCT through Investigador FCT contracts of reference IF/00169/2012, and IF/00028/2014, respectively, and POPH/FSE (EC) by FEDER funding through the program "Programa Operacional de Factores de Competitividade - COMPETE". E.D.M acknowledge the support from the FCT in the form of the grants IF/00849/2015/CP1273/CT0003. JJN acknowledges support from FCT in the form of a "PhD::Space" (PD/00040/2012) network doctoral grant, of reference PD/BD/52700/2014. This research has made use of the SIMBAD database operated at CDS, Strasbourg (France).

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Appendix A: Complete refined line list

The complete refined line list with Solar EWs measured by hand using IRAF.

Table A.1. Refined line list with all Fe I and Fe II lines and corresponding atomic data, including the updated log *gf*. This table is available online.

Wavelength (Å)	Element	EP (eV)	log *gf*	Solar EW (mÅ)
10065.05	Fe I	4.83	-0.279	94.0
10080.42	Fe I	5.10	-1.964	5.9
10081.39	Fe I	2.42	-4.512	6.9
10086.24	Fe I	2.95	-3.978	7.0
10137.10	Fe I	5.09	-1.736	9.8
10142.84	Fe I	5.06	-1.554	14.9
10145.56	Fe I	4.80	-0.118	109.0
10155.16	Fe I	2.18	-4.336	16.2
10156.51	Fe I	4.59	-2.109	12.2
10167.47	Fe I	2.20	-2.319	125.7
10195.11	Fe I	2.73	-3.608	22.6
10216.31	Fe I	4.73	0.047	129.9
10218.41	Fe I	3.07	-2.893	40.9
10265.22	Fe I	2.22	-4.648	8.1
10307.45	Fe I	4.59	-2.432	6.4
10332.33	Fe I	3.63	-3.131	10.5
10340.89	Fe I	2.20	-3.665	46.6
10347.97	Fe I	5.39	-0.717	37.0
10353.81	Fe I	5.39	-0.989	24.2
10364.06	Fe I	5.45	-1.100	18.0
10379.00	Fe I	2.22	-4.236	18.7
10388.75	Fe I	5.45	-1.471	8.7
10395.80	Fe I	2.18	-3.435	61.3
10423.03	Fe I	2.69	-3.658	22.9
10423.74	Fe I	3.07	-3.119	29.9
10469.65	Fe I	3.88	-1.277	89.3
10532.24	Fe I	3.93	-1.650	64.4
10555.65	Fe I	5.45	-1.282	13.1
10577.14	Fe I	3.30	-3.222	17.2
10616.72	Fe I	3.27	-3.306	15.6
10725.19	Fe I	3.64	-2.948	15.7
10753.00	Fe I	3.96	-2.077	39.7
10780.69	Fe I	3.24	-3.553	10.4
10783.05	Fe I	3.11	-2.786	47.0
10818.28	Fe I	3.96	-2.160	35.6
10863.52	Fe I	4.73	-0.877	67.1
10884.26	Fe I	3.93	-2.129	39.1
10896.30	Fe I	3.07	-2.911	42.9
11013.24	Fe I	4.80	-1.240	42.4
11026.79	Fe I	3.94	-2.517	21.2
11119.80	Fe I	2.85	-2.452	84.8
11641.80	Fe I	4.58	-2.116	15.6
11778.42	Fe I	5.34	-1.708	8.4
12053.08	Fe I	4.56	-1.602	41.3
12119.50	Fe I	4.59	-1.897	25.0
12213.34	Fe I	4.64	-2.006	19.1
12227.11	Fe I	4.61	-1.408	51.5
12244.92	Fe I	3.64	-3.222	11.8
12340.48	Fe I	2.28	-4.680	9.4
12342.92	Fe I	4.64	-1.545	42.1
12510.52	Fe I	4.96	-1.930	12.9
12557.00	Fe I	2.28	-4.026	33.8
12615.93	Fe I	4.64	-1.686	35.7
12638.70	Fe I	4.56	-0.679	112.3
12807.15	Fe I	3.64	-2.649	37.1
12808.24	Fe I	4.99	-1.811	16.4
12824.86	Fe I	3.02	-3.612	20.1
12840.57	Fe I	4.96	-1.612	25.3
12879.77	Fe I	2.28	-3.525	68.7
12896.12	Fe I	4.91	-1.713	23.2

Table A.1. continued.

Wavelength (Å)	Element	EP (eV)	log *gf*	Solar EW (mÅ)
12933.01	Fe I	5.02	-1.879	13.9
12934.67	Fe I	5.39	-1.103	30.9
13014.84	Fe I	5.45	-1.542	12.3
13352.17	Fe I	5.31	-0.355	94.4
13392.10	Fe I	5.35	-0.105	115.1
15194.49	Fe I	2.22	-4.808	14.1
15201.57	Fe I	5.49	-1.315	29.0
15207.53	Fe I	5.38	0.311	215.9
15335.38	Fe I	5.41	0.252	205.2
15490.34	Fe I	2.20	-4.787	16.1
15593.74	Fe I	5.03	-1.796	28.0
15611.15	Fe I	3.42	-2.966	51.6
15631.95	Fe I	5.35	0.171	207.0
15648.51	Fe I	5.43	-0.633	93.8
15676.58	Fe I	5.11	-1.848	22.3
16198.50	Fe I	5.41	-0.376	131.4
17420.83	Fe I	3.88	-3.628	6.7
19923.34	Fe I	5.02	-1.536	49.7
21851.38	Fe I	3.64	-3.578	12.7
22257.11	Fe I	5.06	-0.704	132.5
22380.80	Fe I	5.03	-0.377	179.4
22392.88	Fe I	5.10	-1.330	60.8
22619.84	Fe I	4.99	-0.564	158.2
23308.48	Fe I	4.08	-2.705	31.3
10427.31	Fe II	6.08	-1.575	13.7
10501.50	Fe II	5.55	-1.861	19.5
10862.64	Fe II	5.59	-2.006	15.3
11125.58	Fe II	5.62	-2.213	10.5
13251.14	Fe II	9.41	0.768	13.4