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High resolution near-IR spectroscopic stellar characterization: Refining an iron line list

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ABSTRACT

Stellar atmospheric parameters for FGK stars are commonly obtained using high resolution and high S/N optical spectroscopy. The advent of a new generation of high resolution ($R > 50\,000$) near-IR spectrographs opens the possibility of using classic spectroscopic methods with high resolution and high S/N in the NIR spectral window. We aim to refine a NIR iron line list used for the determination of stellar atmospheric parameters using an Equivalent-Width method. To test the new line list we derive parameters of two K giant stars, Arcturus and 10 Leo. The spectroscopic analysis applied here is based on the iron excitation and ionization balance assuming LTE and a new line list of Fe I and Fe II lines in the NIR domain. The line list is being refined from our previous study so it can now be applyed to a wider range of stars. We present an updated list of lines in the NIR that allow us to successfully obtain parameters from NIR spectroscopy for two K giants. With these positive results our goal is to extend the method towards cooler stars, thus allowing us to explore the M dwarf stars in the future. The improvement of the derivation of stellar parameters for M dwarfs is very important for the study of the Galactic Chemical Evolution and crucial for the characterisation of many Earth-like planets, expected to be very common around these kind of stars.

Key words: stars: fundamental parameters – techniques: spectroscopic – methods: data analysis – stars: abundances

1 INTRODUCTION

The study of stellar atmospheric parameters have always been important in astronomy. These parameters consists of e.g. the effective temperature, the surface gravity, the chemical composition of the stellar atmosphere, and the overall metallicity (where [Fe /H] is often used as a proxy). These, or a subset of these, can be derived with many different methods such as, but not limited to, the infrared flux method (IRFM) (Blackwell & Shallis 1977), temperature-metallicity-colour correlations (see e.g. Ramírez & Meléndez 2005), asteroseismology (see Kjeldsen & Bedding 1995, for a classic example), and different spectroscopic approaches such as synthetic fitting (see e.g. Önehag et al. 2012; Tsantaki et al. 2017) and curve-of-growth analysis (see e.g. Sousa et al. 2008; Andreasen et al. 2017).

Not all the methods provide the same information, for example asteroseismology alone can not provide information of $T_{\rm eff}$ but is in turn dependent on this parameter. On the other hand it is also well known that the surface gravities provided by asteroseismology are typically more reliable than those from spectroscopy alone (see e.g. the discussion by Mortier et al. 2014).

The derivation of stellar atmospheric parameters can be used to benchmark stellar evolutionary models, the study of different galactic populations and the galactic chemical evolution, and in recent years to study star-planet correlations. With the advance of high precision instruments, we have open entire new windows into the study of stellar astrophysics with e.g. the *Kepler* and *CoRoT* space missions (see e.g. Christensen-Dalsgaard et al. 2010; Chaplin et al.

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2011; Huber et al. 2014), and spectrographs like HARPS for searching new exoplanets (Mayor et al. 2003) and UVES (Dekker et al. 2000).

In recent years there has been an emphasis on exploring the near-IR (NIR) domain of the spectrum with high-resolution spectrographs ($R \geq 50\,000$). These includes the GIANO spectrograph installed at *Telescopio Nazionale Galileo* (TNG) (Origlia et al. 2014), as is the *infrared doppler instrument* (IRD) installed at the Subaru telescope (Kotani et al. 2014), *iShell* at the NASA Infrared Telescope Facility on Maunakea (Rayner et al. 2016), and *Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical échelle Spectrographs* (CARMENES) at the 3.5m telescope at Calar Alto Observatory (Quirrenbach et al. 2014). 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 2018, and 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 very soon, and 3) *Near-InfraRed Planet Searcher to Join HARPS on the ESO 3.6-metre Telescope* (NIRPS) (Bouchy et al. 2017). The spectral resolutions for these spectrographs range between 50 000 and 100 000.

With the advance of the next generation high resolution NIR spectrographs, the community is 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; Passegger 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 in order to make full use of these instruments.

In this paper we continue our study to explore the use of the NIR domain to derive stellar parameters for FGK and M stars using the curve-of-growth analysis with an iron line list, which was initiated in Andreasen et al. (2016) (referred to as Paper I). Here we analyse the atlas of Arcturus and the spectrum of 10 Leo which serves as benchmark for the evaluation of our method and linelist in the NIR. For the analysis we use the iron line list presented in Paper I which we improve and in this work. 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 extending the aplicability of our NIR method. 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 which are more prominent in the optical part for cool stars. Moreover, the coolest 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.

In Section 2 we present the NIR spectra used in this analysis, while we explain how the previous iron line list is being refined in Section 3. The method to obtain the parameters are briefly explained in Section 4 before the results are presented in Section 5. This is finally followed by a discussion in Section 6 and conclusion in Section 7.

2 STELLAR SPECTRA

While the community is currently on the verge to access large amounts of high resolution NIR spectra, the available spectra at start of this work was still very sparse. For Paper I we started with the subgiant HD 20010, a star hotter than the Sun, but still the closest one in terms of spectroscopic parameters, thus making it an ideal first step for our goal. To continue our work we chose here two additional stars with NIR spectra that are cooler than the Sun. The solar spectrum was still used for inspecting the line list presented in Paper I. This spectrum was obtained from the Kitt Peak telescope by Hinkle et al. (1995a).

The spectrum of HD 20010 will be reused as well. This spectrum was obtained with the CRIRES spectrograph by Lebzelter et al. (2012) as part of the CRIRES-POP. HD 20010 will therefore be reanalysed to confirm the the improvement of the refined line list is still consistent for hotter stars.

The two new stars introduced in this work are Arcturus and 10 Leo. They will serve to continue the test of the NIR EW method and the line list that we refine here. These two extra stars significantly increase the range of spectral types, allowing to test cool giant stars with different metallicities regimes.

Arcturus is one of the brightest stars on the Northern hemisphere, and 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 (Jofré et al. 2014; Smiljanic et al. 2014). The atlas of Arcturus (acquired at Kitt Peak National Observatory using the FTS spectrograph at the Mayall telescope by Hinkle et al. (1995b)), 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 made available by 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, due to those gaps and as we will see below, we were unable to measure one Fe II line which are very important to determine the surface gravity with our EW method.

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.

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. Specifically for Arcturus, we use the same parameters as reported in Table 1 in Jofré et al. (2014). These parameters are a mean from the PASTEL catalogue between 2000 and 2012. The parameters are the median values of all measurements for a given star, where the errors reported are the standard deviation of those values. This also explains the slightly higher errors than what is usually possible with a single measurement. ξ_{micro} is estimated using the empirical relation by Tsantaki et al. (2013) for HD 20010, and Adibekyan et al. (2015) for 10 Leo[1]. The first relation by Tsantaki et al. (2013) is only valid for $\log g \geq 3.85$, while the other relation is for giant stars. For Arcturus the value is a mean of the derived microturbulence from different groups as explained in Jofré et al. (2014). 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.

3 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 covers the J band, and which has been tested extensively on CRIRES spectra ($R \sim 100\,000$) using the spectral synthesis method. There is also the work by Shetrone et al. (2015) for deriving parameters of giant stars using the H band in APOGEE spectra also with the spectral synthesis method.

Our goal is to compile an iron line list that is optimised to derive parameters for FGK and possibly M dwarf stars using an EW method which follows the same approach as described in e.g. Sousa et al. (2008). To achieve this we start with the list of NIR lines that we were able to collect using VALD (Piskunov et al. 1995; Kupka et al. 2000) and then applied a selection process to compile the best lines for our method. This was initially done in Paper I as 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 000Å, 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 200mÅ. The oscillator strengths of the line list were calibrated using the solar spectrum, and the solar iron abundance from Gonzalez & Laws (2000) at 7.47 dex. We chose this reference for consistency with our previous works on stellar parameters. Nevertheless, we note that this value is very similar to other more recent values (e.g. Asplund et al. 2009). Since all our analysis is relative to the Sun, this choice has no significantly relevant influence in the final results. The abundances of individual iron lines were then obtained with the radiative transfer code MOOG (Sneden 1973) assuming LTE and using ATLAS model atmospheres (Kurucz 1993). In Paper I the line list was used to derive atmospheric parameters for a late F star, HD20010.

3.1 Refining the NIR line list

In this work we will go one step forward, and test the previous line list for two K giant stars. Our goal is to have a unique line-list that works well for different spectral types. Although this is a difficult task given that the line strengths change with spectral types, we try to keep this as a goal for homogenisation reasons. As a consequence of this, we expect ~~that~~ a decrease of the number of good lines that are measured simultaneously for different types of stars. Because of this, and before testing the original line list from Paper I at cooler effective temperatures with two K stars, it was mandatory to first try to refine the line list. This includes identifying recurring outliers (both from the work done in Paper I and in this work), and double check ~~the~~ if there is still lines which ~~we~~ are not good to be measured, e.g. if a line is amidst a forest of telluric lines. These outliers will be easily identified since we now can use three spectra compared to just one in the original work. Another justification to redo this step is because in Paper I we found [Fe /H] values for HD 20010 that were about 0.1 dex higher than those found in the literature which lead us to conclude that we could improve the method. Moreover, since the errors for all the parameters derived in Paper I were significantly higher when compared with what we would expect given our experience in the analysis of the optical spectrum, in the refinement done in this work for the line list we were more rigid in the constrains for the selection of the best lines. This is also another reason for the drastic decrease of the number of lines that we present here.

To identify outliers the solar atlas used in Paper I was revisited. This solar atlas is contaminated with telluric lines and given our new very strong constrains we removed a significant part of the original lines. 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 EW technique of determining atmospheric stellar parameters.

In this process, the EW of the lines in the Solar spectrum were now measured by visual inspection (this had previously been done totally automatically with ARES). This process helped us to better identify the lines that were blended. In cases where there is severe line blending, the line was discarded as described above. Since we re-measured the EWs, the oscillator strengths, $\log gf$, were also re-calibrated again for consistency reasons. Here we simply change the $\log gf$ values for the measured line until the abundance of a given line is equal to that of the Sun, using the a solar atmosphere model, the same as in Paper I. The final revisited line list with the updated $\log gf$ is presented in Table A1.

Our EW method implies the use of Fe II lines to determine $\log g$ by imposing ionization balance with the average Fe I abundance. However, the low number of selected Fe II lines in the NIR is a concern, given that average abundance of Fe II will be more affected by small number statistics compared to the numerous Fe I lines.

[1] The two relations are valid for different evolutionary stages, main sequence stars and giants, respectively.

Table 1. Stellar parameters used as reference in this work.

Star	Spectrographs	Resolution	T_{eff} (K)	$\log g$ (dex)	ξ_{micro} (km/s)	[Fe/H] (dex)
Sun	FTS	600 000	5777	4.44	1.00	0.00
Arcturus (a)	FTS	100 000	4247 ± 37	1.59 ± 0.04	1.30 ± 0.12	-0.54 ± 0.04
HD 20010 (b)	CRIRES	100 000	6152 ± 95	3.96 ± 0.11	1.17 ± 0.24	-0.27 ± 0.06
10 Leo (c)	CRIRES	100 000	4742 ± 61	2.76 ± 0.17	1.45 ± 0.08	-0.03 ± 0.02

The stellar parameters were compiled using the the PASTEL catalogue (Soubiran et al. 2016) (see text for details), except the parameters for the Sun.
(a) - Luck (2015); Ramírez et al. (2013); Massarotti et al. (2008); McWilliam (1990); Soubiran et al. (2008); Griffin & Griffin (1967); Gray et al. (2003); Luck & Heiter (2007); Sheffield et al. (2012); Allende Prieto et al. (2004); Gratton (1953); Schwarzschild et al. (1957); Cayrel de Strobel et al. (1970); Maeckle et al. (1975); Penston et al. (1977); Martin (1977); Oinas (1977); Branch et al. (1978); Cenarro et al. (2007); Lambert & Ries (1981); Gratton et al. (1982); Bell et al. (1985); Gratton & Ortolani (1986); Kyrolainen et al. (1986); Leep et al. (1987); Edvardsson (1988); Fernandez-Villacanas et al. (1990); Brown & Wallerstein (1992); McWilliam & Rich (1994); Sneden et al. (1994); Hill (1997); Gonzalez & Wallerstein (1998); Tomkin & Lambert (1999); Carr et al. (2000); Frasca et al. (2009); Prugniel et al. (2011)
(b) See references in Paper I
(c) Park et al. (2013); Luck (2015); Massarotti et al. (2008); Soubiran et al. (2008); da Silva et al. (2011)

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) 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, ATLAS9 is used here). While this is a well tested method for getting atmospheric parameters utilising the optical part of the spectrum, little work has been done with the EW method in the NIR domain. Therefore we approach the measurements of the EWs with extra care, thus the measurements of EWs were done with both manually (IRAF) and automatically (ARES) as a quality check. For both the automatically and manually measured EWs, we discard at this point all lines with an EW below 5 mÅ and above 150 mÅ before continuing the analysis. We decided to be a bit more constrained in the upper limit for the line strength to be sure that the Gaussian fit is a good approximation. Lines outside this range are either too weak to be reliably measured or saturated. 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. These results serve as a benchmark for the presented NIR EW method and the respective refined NIR line list. We do not derive any parameters for the Sun since the line list is calibrated for this star. The solar parameters used in this process are listed in the Table 1.

5.1 Revisiting HD 20010

As a first step we revisit HD 20010 for which we derived atmospheric stellar parameters using the newly revised line list presented in this paper. The results are shown in Table 2 along with the results for the two other stars analysed in this work. Our new analysis, based on the refined line-list (see above), provides results that are in better agreement with the average literature values adopted (especially $\log g$), and smaller errors with the updated results. This suggests that the new line list is indeed more reliable dispite the significantly lower number of lines used in the anylisis. It shows a clear example that quality can be better than the amount.

The comparison of the derived parameters with those considered as reference, collected from literature, is visualised in Fig. 1. Given the small number of available Fe II lines, we adopted two different methodologies to derive the spectroscopic parameters: deriving all stellar parameters simultaneously (T_{eff}, $\log g$, ξ_{micro} and [Fe/H]) or deriving only

Table 2. NIR Spectroscopic Parameters derived in this work.

	HD 20010	10 Leo	Arcturus
Literature			
T_{eff} (lit.)	6152 ± 95	4741 ± 60	4247 ± 37
$\log g$ (lit.)	3.96 ± 0.19	2.76 ± 0.17	1.59 ± 0.04
[Fe/H] (lit.)	-0.27 ± 0.06	-0.03 ± 0.02	-0.54 ± 0.04
ξ_{micro} (lit.)	1.17 ± 0.24	1.45 ± 0.08	1.30 ± 0.12
$\log g$ fixed			
T_{eff}	6161 ± 164	4761 ± 118	4357 ± 74
$\log g$	3.96 (fixed)	2.76 (fixed)	1.59 (fixed)
[Fe/H]	-0.18 ± 0.11	0.01 ± 0.07	-0.55 ± 0.04
ξ_{micro}	1.72 ± 0.44	1.25 ± 0.11	1.55 ± 0.10
All free			
T_{eff}	6162 ± 184	4805 ± 98	4439 ± 62
$\log g$	4.08 ± 0.77	2.42 ± 0.61	1.20 ± 0.20
[Fe/H]	-0.18 ± 0.11	-0.01 ± 0.07	-0.58 ± 0.06
ξ_{micro}	1.59 ± 0.49	1.23 ± 0.10	1.55 ± 0.10

Note: Results for the three stars with first set of parameters are the literature values as presented in Table. 1, second set of parameters are results with $\log g$ set to the same value during the minimization procedure as found in the literature (fixed), and last set of parameters are with all parameters free during the minimization procedure.

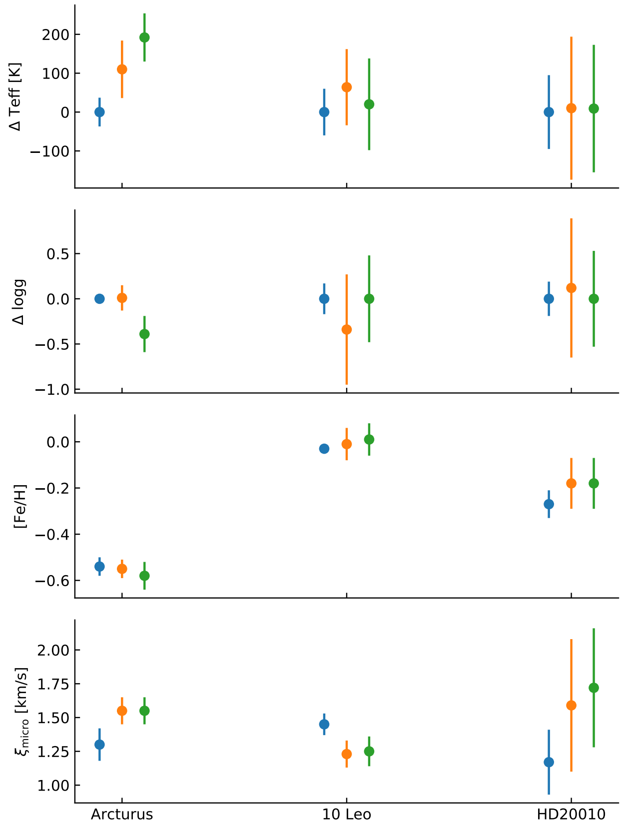

Figure 1. Parameters for Arcturus, 10 Leo, and HD 20010 (revisited in this paper). The blue points show the referece values as discussed in the text. The orange points are the derived values with $\log g$ fixed to the literature value, and the green points show the derived parameters when $\log g$ is also derived. For T_{eff} and $\log g$ the results are shown compared to the literature value to see the difference.

T_{eff}, ξ_{micro}, and $[\mathrm{Fe/H}]$ but constraining the $\log g$ to the reference value. The latter approach does not make use of any of the Fe II lines. In the figure we show the reference values (blue - listed in table 1), the derived parameters with $\log g$ fixed to the reference value for each star (green), and the derived parameters with $\log g$ is free during the minimization procedure (red points).

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 with a mean difference of 3%. This means that the EWs measured

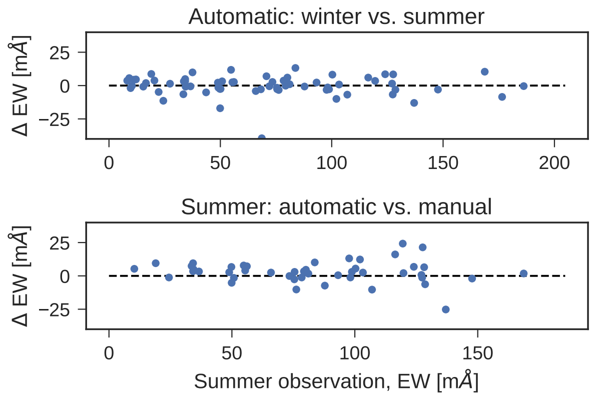

Figure 2. Top figure: Difference of the automatic EW measurements between the summer observations and winter observations from the Arcturus spectra. Bottom figure: Same as above, but with manual measurements from ARES (summer) and automatic measurements (summer).

from the two data sets are very similar, and thus was enough to manually measure the EWs for our lines for only one set (summer). However, we did measure a few lines from the winter data set to certify a good agreement. Since the automatic EWs are very similar to the manual ones we chose to only derive parameters of the summer set with EWs measured with ARES.

Due to the low number of pressure sensitive Fe II lines we again derive parameters with and without $\log g$ set to a fixed reference value (1.59 dex, the average literature value adopted). The derivation of the parameters followed the procedure presented Andreasen et al. (2017) with the minimization routine `FASMA`. After we reached convergence using all the iron lines we were able to identify any outlier above 3σ in abundance. The outliers were removed one-by-one, followed by the restarting of the minimization routine. This process was done iteratively until there were no more outliers. The final results are presented in Table 2 together with reference parameters from the literature.

From our analysis with $\log g$ fixed we derive a T_{eff} 100 K higher than the reference, which is just within the errorbars. When $\log g$ is also set as a free parameter, we see a 200 K difference. From this second analysis we also derive a $\log g$ that is ~ 0.4 dex below the reference value. On the other hand, the $[\mathrm{Fe/H}]$ value we derived is in very close agreement with the literature values: only 0.04 dex distant when $\log g$ is fixed, and 0.10 dex otherwise. The value in both cases are well within the errors of the literature value.

5.3 10 Leo

The approach for determining the atmospheric stellar parameters for 10 Leo is identical to Arcturus, although we did not measure any EWs by hand here. 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 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 final results can be seen in Fig. 1 and Table 2.

Generally the derived parameters are in excellent agreement with the literature values listed here. For $T_{\rm eff}$ we were 64 K off with $\log g$ set as a free parameter, well within the errors. The only parameter that show a discrepancy compared to the reference value is $\xi_{\rm micro}$ with a difference of 0.22 km/s, which is at the limit of the errors reported. We note that this parameter is not reported in the PASTEL database, and this was a derived parameter from an empirical relation. We were able to derive good $\log g$ values, although with larger errors compared to the results from the literature.

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). Moreover, this is not possible for all spectral classes. It is e.g. not possible for M dwarfs, since no pulsations have been observed here.

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] for Arcturus 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.

Furthermore, 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 9.7 mÅ (in Arcturus), while the highest measured value is only 24.4 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 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 original derived line list used, which we improve in this work. 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.

6.3 The refined line list

The line list from Paper I has been refined, i.e. several blended or otherwise unreliable measured lines have been removed. Many of these lines were not identified in the previous work since we applied an automatic approach, mainly due to the extreme large amount of iron transitions available in the YJHK bands. The new line list provides better results for HD 20010. Furthermore, the refined line list was tested on the two additional K giants, Arcturus and 10 Leo. We see a good agreement between the derived parameters and the literature values used for comparison. During the spectroscopic analysis of these stars we have additional identified two lines as outliers in Table A1. These lines are the two Fe I lines at 10167.47 Å and 11641.80 Å.

7 CONCLUSION

In this paper we presented a refined Fe I and Fe II line list in the NIR domain to derive parameters for high resolution spectra. The method should work in all spectral ranges, however, it was important to identify the best 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 spectroscopic parameters can now be applyed to NIR spectra as well. The refined line list has been used to sucessfully derive 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 reference 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 new spectral library from CARMENES[2] (Reiners et al. 2017) will provide the community with high quality spectra and allow us to extend our test to many different spectral types of interest.

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[2] This library was not available when this work was carried out.

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APPENDIX A: COMPLETE REFINED LINE LIST

The complete refined line list with Solar EWs measured by hand using IRAF, and the three stars also analysed in this work. Note that the EWs given here are after removal of outliers in abundance. This is done automatically with `FASMA` (Andreasen et al. 2017).

Table A1. Refined line list with all Fe I and Fe II lines.

Wavelength (Å)	Element	EP (eV)	$\log gf$	Sun	HD 20010	10 Leo	Arcturus	Giant outlier
10065.05	Fe I	4.83	-0.279	94.0	...	115.2	107.0	no
10080.42	Fe I	5.10	-1.964	5.9	...	...	...	no
10081.39	Fe I	2.42	-4.512	6.9	...	42.9	49.8	no
10086.24	Fe I	2.95	-3.978	7.0	39.5	34.2	...	no
10137.10	Fe I	5.09	-1.736	9.8	...	21.1	12.1	no
...	...	...	...	...	...	...	...	..

This table contains the atomic data, including the updated $\log gf$. The fifth to the eight columns are the measured EWs in mÅ for the four stars analysed in this work. **The last column shows where Arcturus and 10 Leo both had outliers in the derivation of parameters.** This table is available in an electronic form online.

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