

# High resolution near-IR spectroscopy of Arcturus and 10 Leo

## Refining a near-IR iron line list

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### ABSTRACT

**Context.** Effective temperature, surface gravity, and metallicity are basic spectroscopic stellar parameters necessary to characterize a star or a planetary system. Reliable atmospheric parameters for FGK stars have been obtained mostly 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 compile a new iron line list in the NIR from a solar spectrum to derive precise stellar atmospheric parameters, comparable to the ones already obtained from high resolution optical spectra. The spectral range covers 10 000 Å to 25 000 Å, which is equivalent to the Y, J, H, and K bands.

**Methods.** Our spectroscopic analysis is based on the iron excitation and ionization balance done in LTE. We use a high resolution and high signal-to-noise ratio spectrum of the Sun from the Kitt Peak telescope as a starting point to compile the iron line list. The oscillator strengths ( $\log gf$ ) of the iron lines were calibrated for the Sun. The abundance analysis was done using the MOOG code after measuring equivalent widths of 357 solar iron lines.

**Results.** We successfully derived stellar atmospheric parameters for the Sun. Furthermore, we analysed HD20010, a F8IV star, from which we derived stellar atmospheric parameters using the same line list as for the Sun. The spectrum was obtained from the CRIRES-POP database. The results are compatible with the ones found in the literature, confirming the reliability of our line list. However, due to the quality of the data we obtain large errors.

**Key words.** data reduction: high resolution spectra – stars individual: Arcturus – stars individual: HD010853

## 1. Introduction

Effective temperature ( $T_{\text{eff}}$ ), 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 determine other indirect fundamental parameters such as mass, radius, and age from stellar evolutionary 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 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. Santos et al. 2013). Interferometry is usually considered an accurate method for deriving stellar radii (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 the mass and radius (e.g. Kjeldsen & Bedding 1995).

A crucial parameter for the indirect determination of stellar bulk properties is the effective temperature. In that respect, the infrared flux method (IRFM) has proven to be reliable for FGK dwarf and subgiant stars. However, 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, and wavelength region. For low resolution spectra ( $\lambda/\Delta\lambda < 20\,000$ ) the preferred method is to fit the overall observed spectrum with a synthetic one (see e.g. Recio-Blanco et al. 2006). Higher resolution spectra of slowly rotating stars (below 10 to 15 km/s) are in the regime where the equivalent width (EW) method can be used (see e.g. ?, for details).

The derivation of stellar atmospheric parameters from high resolution spectra in the optical is now based on a standard procedure (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; Muccia-

relli et al. 2013; Bensby et al. 2014). At the moment, the GIANO spectrograph installed at *Telescopio Nazionale Galileo* (TNG) is already available (Origlia et al. 2014), the *infrared doppler instrument* (IRD) installed at the Subaru telescope (Kotani et al. 2014), as is *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). Two 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, 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 in 2017 as well. The spectral resolutions for these spectrographs range between 50 000 and 100 000.

With the advance of NIR spectrographs, we are yet to be ready for the analysis of the data arriving at the moment and in the future. 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 this work we analyse the atlas of Arcturus (K0III) and the spectrum 10 Leo (K1III). The atlas of Arcturus was aquired at Kitt Peak National Observatory using the FTS spectrograph at the Mayall telescope (Hinkle et al. 2003) and 10 Leo from CRIRES (Nicholls et al. 2016). For the analysis we use the iron line list presented in Andreasen et al. (2016). This work serve as a continuation of our previous work.

The paper is organized as follows. In Sect. 2 we present the data we have aquired for this work along with some information of the two stars we will analyse. in Sect. 3 we refine the iron line list in order to get more reliable stellar parameters. The results are presented in Sect. 4 before we discuss our results in Sect. 5.

## 2. Data

While the community is currently on the verge to access of a large amount of high resolution NIR spectra with e.g. the spectrographs used here, the available spectra at the moment are sparse. We chose to use two stars cooler than the Sun since we showed in Andreasen et al. (2016) that this method works for a star hotter than the Sun (HD20010).

We have collected the atlas of Arcturus, 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 a few). We use the atlas from Hinkle et al. (2003) 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 second spectrum we have achieved is from the CRIRES-POP team (Nicholls et al. 2016). 10 Leo is a very similar star to Arcturus, which is also one reason this star was the first to be fully reduced by the team. It is a great help to be able to compare with the atlas of Arcturus. The main difference is the metallicity of the two stars, where Arcturus is metal poor and 10 Leo has solar metallicity. The fully reduced spectrum of 10 Leo is also telluric corrected using molecfit (Smette et al. 2015; Kausch et al. 2015). There are a few gaps in the spectrum. This is either due to a telluric that could not be properly removed, low S/R, bad pixels, etc. Rather than giving an uncertain interpolation, Nicholls et al. (2016) decided to leave small gaps in the data. This have very little affect on this analysis. However, we were unable to measure one Fe II line, which are very important to determine the surface gravity.

A small summarise of the data is given in Tab. 1.

## 3. Refining the NIR line list

Besides testing the line list at cooler effective temperatures with two K stars, we also want to refine the line list. This includes identifying recurring outliers, and lines which we are not able to measure, e.g. if a line is amidst a forrest of telluric lines. Hence, de-blending is nearly impossible.

## 4. Results

We derive the stellar atmospheric parameters in a similar way as described in Andreasen et al. (2016) using FASMA (?).

### 4.1. Arcturus

Arcturus is one of the brightest stars on the night sky with a V magnitude of -0.05 (Ducati 2002). Hence it has been subject to numerous observations (add some nice references here...) and is therefore a prime target for testing the line list by Andreasen et al. (2016).

Lines blended with telluric were omitted from the analysis. The equivalent width (EW) of rest of the lines were measured by hand using the *splot* function in IRAF. In the atlas there exist both a summer observation set and a winter observation set. This is in order to minimize the effect of tellurics at different spectral regions. As many lines as possible were measured in both sets, and combined to the final measure line list.

The derivation of the parameters follow exactly the same procedure as used in Andreasen et al. (2016).

### 4.2. 10 Leo

## 5. Conclusion

Being able to successfully determine parameters for two early K giants, we are now making the bridge for the line list towards cooler temperatures. The obvious next step is the even colder M stars. Particular interesting are the M dwarfs known to be prone forming rocky planets.

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**Table 1.** The spectra and spectral type (from Simbad) of our sample with the corresponding spectrograph used to acquire the data and its spectra resolution. In the last column we show the SNR measured with `splot` in IRAF.

Star	Spectral type	Spectrograph	Resolution	SNR
Arcturus	K0III	FTS	100 000	300
10 Leo	K1III	CRILES	100 000	300

**Table 2.** The derived parameters for Arcturus with fixed surface gravity cut after  $3\sigma$  outlier removal. `linelist: arcturus2Cut4ol.moog`

	$T_{\text{eff}}$ (K)	$\log g$ (dex)	$\xi_{\text{micro}}$ (km/s)	[Fe/H] (dex)
Literature	$6131 \pm 255$	$4.01 \pm 0.60$	$1.90 \pm 1.08$	$-0.23 \pm 0.14$
	$4363 \pm 75$	1.59 (fixed)	$1.25 \pm 0.07$	$-0.34 \pm 0.03$

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