Characterizing U-Ne hollow cathode lamps at near-IR wavelengths for the CARMENES survey

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ABSTRACT

Hollow cathode lamps of U and Th are the standard frequency calibrators in astronomical spectrographs. In an effort to optimize precision radial velocity measurements at near-IR wavelengths for the CARMENES survey, we are characterizing 12 commercial U-Ne hollow cathode lamps using a high resolution Fourier Transform Spectrograph and an InGaAs detector to analyze the wavelength range between 950 and 1700 nm. We have recorded spectral atlases of U-Ne operated at 8, 10 and 12 mA, which are typical values used at astronomical observatories in order to maximize lamp lifetimes. In addition to the spectral atlas, we analyze properties like warm-up times, average intensities from lines of different elements, positions and the width of emission lines, and blends. None of our lamps show strong peculiarities in the spectra or significant contamination. The identification of the uranium lines is based on the line widths and consistent with the Redman et al. (2011) catalog. Our line list can add a significant number of lines particularly in the range around 9000 cm^{-1} (1.1 µm) where the catalog is incomplete because of limited detector sensitivity. We are able to identify the elements emitting additional lines by measuring the line width. The increased number of U lines at wavelengths relevant to radial velocity surveys can yield a significant improvement in the accuracy of radial velocity measurements.

Keywords: wavelength calibration, hollow-cathode-lamps, échelle spectrograph, frequency standards, radial velocity technique

1. INTRODUCTION

The stabilization of high resolution échelle spectrographs has advanced many astronomical fields, such as the search for exoplanets. This improvement has resulted in the development of even more sophisticated methods for wavelength calibration using Fabry-Perot (F-P) etalons[1] or laser frequency combs[2]. However, for absolute wavelength calibration the use of hollow cathode lamps (HCLs) is still the preferred strategy. The wavelength calibration of the *Calar Alto High-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs*, CARMENES[3], will use a passively stabilized F-P etalon[4] for nightly drift check and a hollow cathode lamp (HCL) as a standard absolute reference (Th-Ne for the visible channel and U-Ne for near infrared channel). In this article, we describe our efforts to characterize the HCLs for CARMENES.

HCLs are the most common wavelength calibrators for astronomical échelle spectrographs like the *CRyogenic high-resolution InfraRed Échelle Spectrograph* (CRIRES[5]) or the *High Accuracy Radial Velocity Planet Searcher* (HARPS[6]). The main features of HCLs have been analyzed in depth[7]. The HCLs manufacturing process is very delicate[7] (e.g. cathode geometry, contaminants, pressure, etc), therefore characterization of every single HCL is advisable. The HCLs used for ground-based astronomical purposes have a single element cathodes using, e.g., thorium or uranium. There are lines lists available for thorium[8] and uranium[9] that can be used for line identifications.

In the following methodology section, we show our present work on the characterization of U-Ne HCLs including the construction of spectral atlases for different operational currents. In the results section we present our preliminary results. We have found a considerable number of uranium lines in the region where the reference uranium catalog[9] has a lack of sensitivity. Our line list can significantly increase the accuracy of the calibration for the échelle spectrographs in this region. This is particularly interesting because spectra of low-mass M-type stars carry especially much radial velocity information in this region[10]. We also observe that the intensity of the emission lines of 12 lamps from the same batch have very similar behavior with very little variation.

2. METHODOLOGY

2.1 General considerations about the experiments

We have characterized 12 commercial *Photron* U-Ne HCLs for the nIR calibration unit of the CARMENES project[3]. They belong to the same batch and have consecutive serial numbers. We use our *Bruker IFS 125 HR* spectrograph, a high resolution (HR) Fourier Transform Spectrograph (FTS) with a maximum optical path difference of 208 cm. We aim to obtain an emission line list of the commercial HCLs and to verify the status of every single lamp for the CARMENES survey.

The lamps are placed in a housing designed and built by the Thuringian State Observatory workshop **(**Figure 1). The housing has three screws (number 2) for accurately focusing the cathode by moving the housing along the lamp's symmetry axis, and three other screws (number 1) for aligning the lamp in the plane perpendicular to that axis.

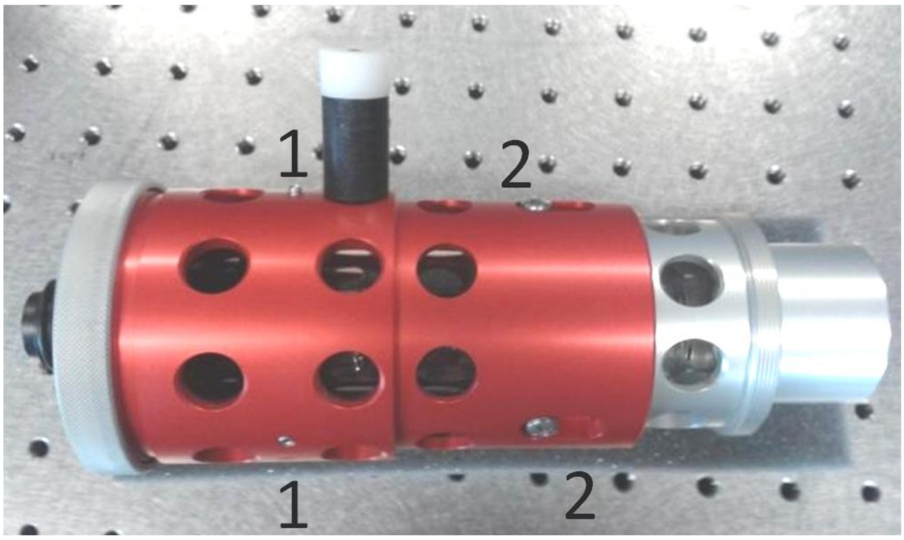

Figure 1. HCL housing built in the Thuringian State Observatory workshop. Numbers indicate the three screws for alignment (1) and three screws for focusing (2).

The fore-optics system consists of the same elements that will be used for the CARMENES calibration unit in order to have the same behavior as in the observatory. It also includes a very simple method for aligning and focusing the light source onto the fiber. The system uses two doublets to reimage the cathode onto the fiber input face, which is connected with a SM1SMA fiber adaptor. A fiber feeds the light into the FTS parallel port (see Figure 2).

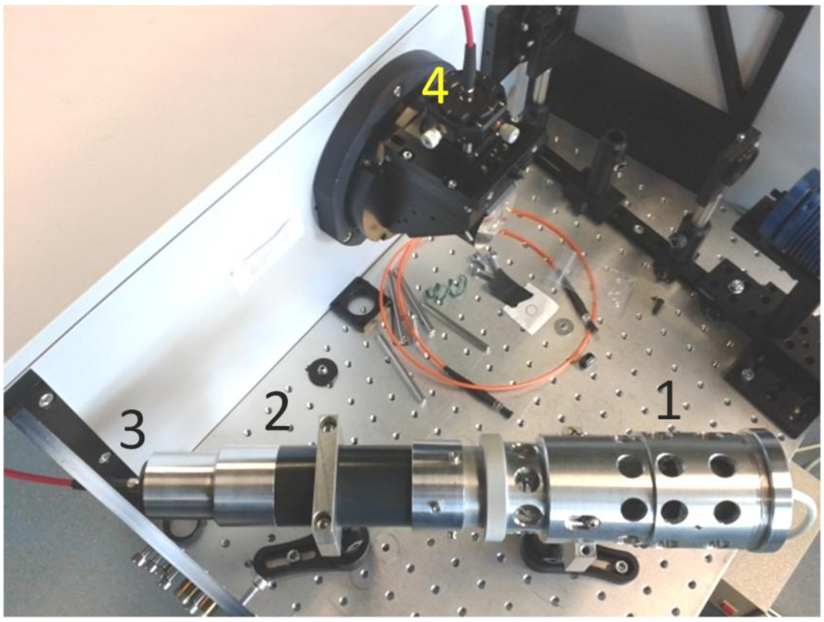

Figure 2. Alignment tool. 1) U-Ne HCL+housing. 2) Optical alignment tool. 3) Fiber input. 4) FTS parallel port.

We evacuated the FTS compartment for at least 3 hours until it reached a stable pressure lower than 0.1 hPa. The HCLs emitted a constant flux after being warmed up for 30 minutes.

The spectral region of interest is located between 5000 cm^{-1} (~ 0.833 µm) and 12000 cm^{-1} (2 µm). The FTS is operating with a CaF_2 beam-splitter and an InGaAs detector. We used a long pass filter (>650 nm) to remove possible features caused by the internal He-Ne laser that defines the spectrograph's frequency solution. We corrected sensitivity variations introduced by the fore-optics, the FTS optics elements and the detector by recording 30 low resolution scans of a tungsten lamp just before and after the measurements.

The wavelength solution of the HR FTS is driven by a He-Ne laser. It is documented[11] that the light source of analysis and the laser light paths could differ slightly in addition to the effect of the limited size of the aperture. This effect introduces either a small compression or stretching of the spectrum's wavelength solution relative to the solution provided by the laser. It is possible to correct this effect by using standards lines, for example the ones measured in optogalvanic spectra using a F-P wave-meter (eight standard lines in the region between 694 nm and 755 nm[12]). The correction of the wavelength solution will not introduce differences in the results shown in this article. No further considerations regarding the wavelength solution correction are considered here.

2.1.1 Experiment 1: Emission line list for the CARMENES survey.

We recorded spectral atlases of one U-Ne HCL operated at 8, 10 and 12 mA. The HCL could be operated at higher operational currents, but using a lower value increases their lifetimes[7]. This is the main reason why these are the typical current values for HCL operated at astronomical observatories.

We measured 150 scans (8 hours-long measurement), which were co-added and Fourier transformed using the commercial OPUS software. Norton-Beer-Medium apodization was applied. The spectra were recorded between 0 cm^{-1} and 30.000 cm^{-1} at a resolution of 0.01 cm^{-1} at a maximum aperture of 1 mm. We used a 400 µm fiber core diameter to feed the light into the spectrograph.

2.1.2 Experiment 2: Status of every single HCL

We recorded a spectrum of every lamp operated at 6 mA as foreseen for their use during CARMENES operation. HCLs at this operational current emit relatively little flux, which means that integration times required are rather long (e.g. ~10 hours) for FT spectroscopy at ultra-high resolution. To minimize the usage of the 12 lamps we increased the SNR of the spectra by using a bigger aperture (2 mm), which limits the FTS resolution to 0.035 cm^{-1}. We used a 910 µm fiber core diameter to feed the light into the spectrograph. For every lamp we recorded 120 scans (2 hours integration time) between 0 cm^{-1} and 30.000 cm^{-1}.

2.2 Data analysis

The method used to analyze the main features (e.g. line position, line intensity, full width at half maximum (FWHM), blends, emitter element, contaminants) of the recorded spectra is the same for both experiments. The main tasks performed can be summarized as peak finding, peak fitting-identification and intensity calibration.

2.2.1 Peak finding

A MatLab-based code was used to detect the emission lines. We measured the noise level of the spectrum by removing the lines of the spectrum and calculating the standard deviation of the remaining points. All local maxima with intensity higher than three times the standard deviation were named as preliminary detected emission lines. We defined groups of points (e.g. 12, 14 size depends on the resolution and the FT zero filling factor selected) around the preliminary detected lines for their fitting. These groups were filtered by imposing two criteria: only the points with intensity higher than the 25 per cent of the maximum intensity of the preliminary detected line are kept and only those with positives slope on one side of the maximum and negative in the other side are accepted in order to remove effects from blends.

2.2.2 Peak fitting and identification

We fit a Gaussian to the preliminary detected lines by applying the logarithm into the intensity values and then fitting a second order polynomial. From the fitting we can infer the three parameters determining the Gaussian curve: center of the curve, maximum value and standard deviation (related to FWHM). To determine the species, we first compare the calculated position with the position found in the catalog (uranium[9], neon[13]). If the distance between the line position from the data base and the calculated position is smaller than three standard deviation of the Gaussian fit, a preliminary identification is done. While the HCLs mainly have emission from the material of the cathode (uranium) and the fill gas (neon), some contaminants from the manufacturing procedure could be present: we have removed such contributions by identifying any nitrogen and argon emission lines.

Uranium and neon have very different atomic weights, which mean that both elements will have emission lines with very different FWHM due to thermal broadening. Using this fact, we re-analyze the emitter element by making a second order polynomial fit of the width of the identified lines: The lines with FWHM larger than 3 times the standard deviation of the fitting are removed from the identified emission line list.

We found a large number of lines that remain unidentified during our data analysis. An important number of them have FWHM comparable to the width of a uranium emission line, but these lines do not appear in the catalogs[9, 13].We will refer to them in the following subsection 3.1 as “U I detected lines”.

2.2.3 Intensity calibration

The spectrum was radiometrically calibrated by dividing the calculated intensities of the lines by the tungsten lamp spectra recorded at low resolution. All the spectra were then normalized by division with the continuum emitted by the cathode obtained by adjusting a straight line to the mean value measured in different regions of the spectra. As the emission lines are very narrow, the continuum correction can be applied on the calculated lines intensity.

3. RESULTS

In the following, we present preliminary results from our U-Ne HCL characterization.

3.1 Results from experiment 1: Emission line list for the CARMENES survey

Table 1 shows the number of identified emission lines in the spectra recorded using different operational currents. The number of uranium lines identified increases substantially when increasing the operational current. Nevertheless, the number of neon lines identified remains essentially constant.

Table 1. Number of emission lines identified emitted by different elements using different operational current.

Operational current (mA)	Element	# Identified lines
8	U	1695
	Ne	174
10	U	2678
	Ne	182
12	U	3712
	Ne	184

Of all the identified lines, we use only the emission lines identified in all three measurements (i.e. 1695 uranium I lines and 129 neon I lines) to analyze the behavior of the lines emitted by uranium and the lines emitted by neon for different operational currents. Fig. 3 shows the averaged intensity of these lines normalized to the averaged intensity measured by operating the lamp at 10 mA. We found different behaviors of the uranium metal lines (represented with a cross symbol) and the neon gas lines (represented with a plus symbol): Uranium lines have a higher relative increment of intensity than neon lines when the operational current increases. This result is in good agreement with the results[7] for Th-Ar HCL operated at 4, 6, 8, 10, 12 and 14 mA. This enables us to double check either for identified lines with ambiguous identification or detected lines that do not appear in the catalogs[9, 13].

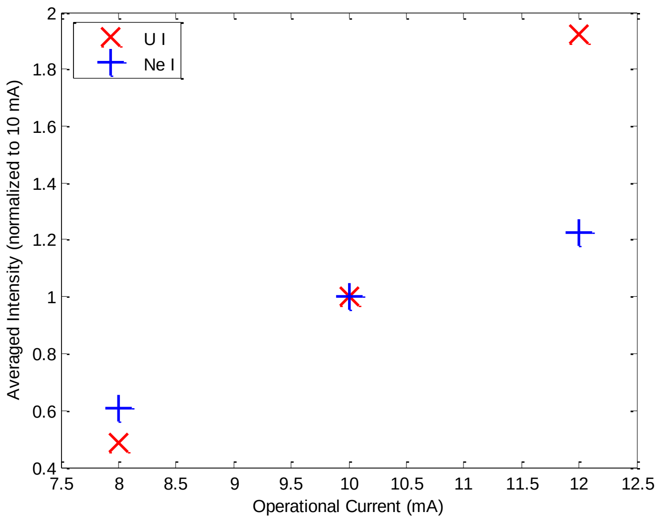

Figure 3. Values on y-axis are normalized to the value obtained using 10 mA operational current. We observe a different behavior of the averaged line intensity strength for emission lines emitted by the metallic element or the fill gas.

During the analysis of the different spectra we detected a considerable number of lines that we could not identify because they do not appear in the catalog[9] or the distance between the position in the catalog and the calculated position was larger than 0.01 cm^{-1}. We carried out a deeper analysis using the spectra recorded when we operated the lamp at 12 mA. In that spectrum, we detected 2578 lines which were not identified. To get a better understanding of those detected lines, we analyzed the intensity of the emission lines in the spectral region of interest with FWHM comparable to uranium because these are the lines which we are interested in for calibration. In Fig. 4, empty squares represent the identified uranium lines (i.e. they are in the catalog[9]) and filled circles represent the detected lines with FWHM comparable to the uranium lines that do not belong to the catalog[9]. There are three areas of special interest in Figure 4: (*i*) we observed an upper limit for the identified emission lines in the catalog (the dash-dotted line from 0.8 arbitrary units at 6000 cm^{-1} to 2.5 arbitrary units at 10500 cm^{-1}). We have detected approximately 50 lines above this upper limit. Those lines were also detected in the spectra recorded operating the lamps at 8 mA and 10 mA, (*ii*) we also observed a very high number of lines around the limit of sensitivity of our experiment (e.g. bottom envelope in Fig. 4). These are low intensity and noisy lines, and their positions are calculated with low accuracy. This fact could introduce a mismatch between the calculated position and the position from the catalog[9]. Most of these lines were not detected in the spectra recorded operating the lamps at 8 mA and 10 mA, (*iii*) in the region where the catalog lacks lines because of reduced sensitivity (between 8700 and 9700 wavenumbers, 1.03-1.15 μm, covering the *Y* band 0.9-1.1 μm which is of special importance for astronomical observations of M dwarfs[10]), we have detected 807 lines. Of those lines, 170 lines were also detected in the spectra recorded operating the lamps at 8 mA and 10 mA. The uranium catalog[9] has 492 emission lines in this spectral region, which means that the number of lines is approximately doubled, which will significantly improve the accuracy of the calibration for the échelle spectrographs in this region.

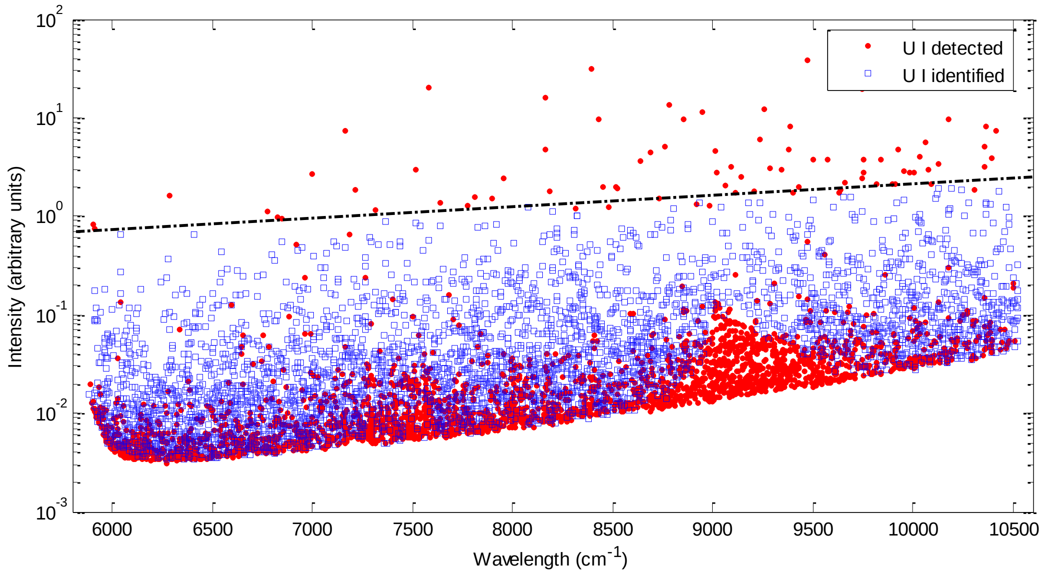

Figure 4. Identified U I lines (in the catalog[9]) empty squares, detected U I lines with FWHM comparable to identified uranium lines full circles.

Note that the observed non-flat bottom slope is not due to the sensitivity of our instrument but comes from the photometric calibration applied using a tungsten lamp, which does not have a flat intensity profile within the spectral range of our analysis.

3.2 Results from experiment 2: Status of every single HCL

To analyze and compare the status of the different U-Ne HCLs under similar operating conditions we firtst analyzed the emission line strength ratios using approx. 250 U I lines identified in all 12 spectra recorded, averaged the intensity of those lines for all the lamps and then calculated the ratio between the intensity of the emission lines for every single lamp with the averaged value. In Fig. 5, we show two plots: on top, we show the distribution of relative intensity between one HCL (HKH0128) and the averaged value in the spectral range of interest; in the bottom, we show the residuals to the linear fit. We observe that the behavior of the lines follow a linear trend (top plot) with rather low scatter. Only a few points show a scatter larger that 10 per cent (bottom plot).

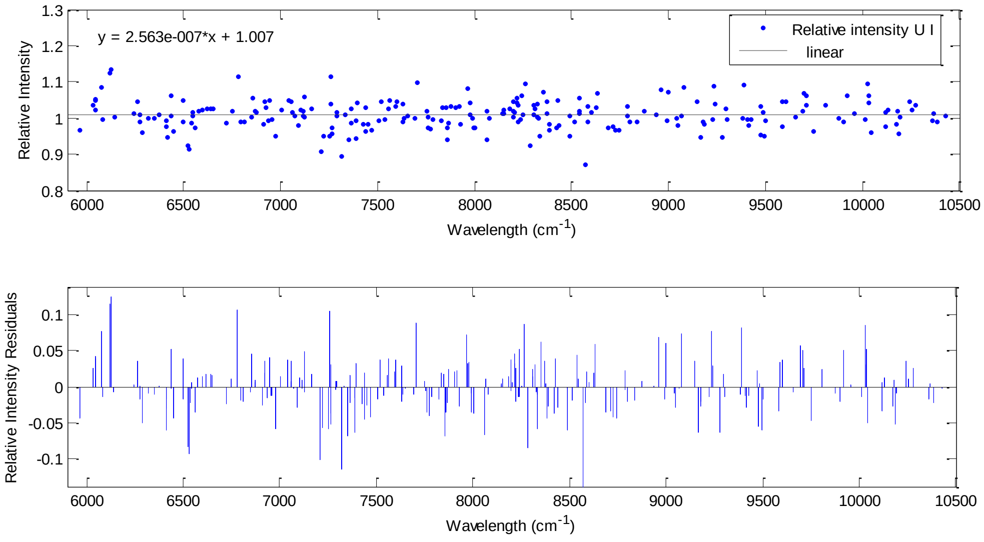

Figure 5. Comparison of the emission lines intensities between one lamp (HKH0128) and the averaged of all the lamps. Top figure shows the relative intensity of every line along the spectral range of interest. Bottom plot depicts the residuals to the linear fit.

We compared the scatter observed in Fig. 5 for all the 12 lamps by calculating histograms of the relative intensity of every one of those lines (250 U I identified in all 12 spectra) for every lamp and adjusted them to Gaussian distributions. With this fitting we obtain the mean value (μ) of the relative intensities and also the standard deviation (σ). This allows us to quantify the scattering around μ. In Table 2 we show the serial number of the lamp and the parameters (μ, σ) obtained for every lamp. The different lamps show slightly different mean relative intensities. Part of this effect is due to the fact that the operational current was not set as accurately as desired. We found that the HCL with higher number of identified lines correspond to the HCL with higher mean values, as expected[7]. We found that all the lamps have a similar behavior showing about 4 % scatter when comparing the relative intensities.

Table 2. Parameters obtained from Gaussian fits of the histograms for the relative intensity between the averaged intensity of all the lamps and single lamps

HCL #	**μ**	**σ (10^{-2})**
HKH0120	0.753	4.2
HKH0121	1.052	3.9
HKH0122	0.842	3.8
HKH0123	0.986	3.5
HKH0124	0.985	3.7
HKH0125	0.869	3.4
HKH0126	0.841	4.4
HKH0127	1.357	3.4
HKH0128	1.007	4.4
HKH0129	1.106	4.1
HKH0130	0.907	3.4
HKH0131	1.278	4.3

4. CONCLUSIONS

The main conclusions of our characterization of CARMENES hollow cathode lamps are the following:

- the 12 lamps are operating as expected; we did not experience failures or significant contamination in our lamps;

- the intensities of uranium lines and neon lines at different operational currents agree with the results for Th-Ar[7]; this can help to identify lines with ambiguous identification;

- when we operated the lamp at 12 mA, we detected 807 new lines with FWHM similar to the identified uranium lines in the region where the most complete uranium catalog[9] contains only 492 lines and has a lack of sensitivity; of those new lines, 170 were also detected in the spectra recorded operating the lamps at 8 and 10 mA;

- within the limited accuracy of the experiment, the lamps show largely comparable relative intensities;

- the 12 lamps have a remarkable reproducibility (about 4 % dispersion with respect to the average).

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REFERENCES

[1] Wildi, F., Chazelas, B. and Pepe, F., "A passive, cost effective solution for the high accuracy wavelength calibration of radial velocity spectrographs" Proc. SPIE Vol. 8446E (2012).

[2] Murphy, M.T., Udem, Th., Holzwarth, R., et al., "High precision wavelength calibration for astronomical spectrographs with laser frequency combs" Mon. Not. R. Astron. Soc. 000, 1-10 (2007).

[3] Quirrenbach, A., Amado, P.J., Seifert, W., et al., "CARMENES. I: instrument and survey overview" Proc. SPIE 84460R, (2012).

[4] Schäfer, S. and Reiners, A., "Two Fabry-Perot interferometers for high precision wavelength calibration in the near-infrared" Proc. SPIE 844694 (2012).

[5] Käufl, H.U., Ballester, P., Biereichel, P., et al., "CRIRES: A High Resolution Infrared Spectrograph for ESO's VLT" Proc. SPIE 5492, 1218 (2004).

[6] Lovis, C., Mayor, M., Pepe, F., et at., [Precision Spectroscopy in Astrophysics] "Pushing Down the Limits of the Radial Velocity Technique", ESO Astrophysics Symposia, 181-184 (2008).

[7] Kerber, F., Nave, G., Sansonetti, C.J., et al., "The spectrum of Th-Ar Hollow Cathode Lamps in the 900-4500 nm Region: Establishing Wavelength Standards for the Calibration of VLT Spectrographs" ASP Conference Series, Vol. 364, 461-478 (2007).

[8] Redman, S.L., Nave, G. and Sansonetti, C.J., "The spectrum of Thorium from 250 nm to 5500 nm: Ritz wavelengths and optimized energy levels" ApSJ 211 4 (2014).

[9] Redman, S.L., Lawler, J.E., Nave, G., et al., "The infrared Spectrum of Uranium Hollow Cathode Lamps from 850 nm to 4000 nm: Wavenumbers and Line Identifications from Fourier Transform Spectra" ApJS 195 24 (2011).

[10] Reiners, A., Bean, J.L., Huber, K.F., et al., "Detecting planets around very low mass stars with the radial velocity method" ApJ, 710, 432-443 (2010).

[11] Davis, S.P., Abrams, M.C. and Brault, J.W., [Fourier Transform spectrometry], Academic Press, California and London, 143-168 (2001).

[12] DeGraffenreid, W. and Sansonetti, C.J., "Reference lines in the optogalvanic spectra of uranium and thorium over the wavelength range 694-755 nm" JOSA B, Vol. 19, Issue 7, 1711-1715 (2002).

[13] Kramida, A., Ralchenko, Yu., Reader, J. and NIST ASD TEAM (2013), "NIST Atomic Spectra Database (ver. 5.1)" (6 June 2014) http://physics.nist.gov/ASD.