WAVELENGTH CALIBRATION OF THE HAMILTON ECHELLE SPECTROGRAPH

YU. V. PAKHOMOV1 AND G. ZHAO2

1 Institute of Astronomy, Russian Academy of Sciences, Moscow, Russia; pakhomov@inasan.ru
2 Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China

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ABSTRACT

We present the wavelength calibration of the Hamilton Echelle Spectrograph at Lick Observatory. The main problem with the calibration of this spectrograph arises from the fact that thorium lines are absent in the spectrum of the presumed ThAr hollow-cathode lamp now under operation; numerous unknown strong lines, which have been identified as titanium lines, are present in the spectrum. We estimate the temperature of the lamp’s gas which permits us to calculate the intensities of the lines and to select a large number of relevant Ti i and Ti ii lines. The resulting titanium line list for the Lick hollow-cathode lamp is presented. The wavelength calibration using this line list was made with an accuracy of about 0.006 Å.

Key words: catalogs – instrumentation: spectrographs – line: identification

Online-only material: machine-readable and VO tables

1. INTRODUCTION

Hollow-cathode lamps produce a great number of lines in the optical band which makes them indispensable for accurate wavelength calibration of echelle spectra. The essential prerequisite for such calibration, however, is knowledge of the wavelengths of reference spectral lines with an accuracy better than the resolution, \( \delta \lambda \sim 0.1 \lambda / R \). Usually, the same line list for this particular type of lamp is used in the data reduction of spectral observations.

On 2012 September 1, spectra of 18 stars were taken on the Shane 3 m telescope of Lick Observatory using the Hamilton Echelle Spectrograph (title of the proposal “A systematic study of NLTE abundance of nearby dwarfs,” PI: G. Zhao, NAOC, China). A resolving power of \( R \approx 60,000 \) and a CCD e2v CCD203-82 \((4k \times 4k, 12\mu, \text{Dewar} \ 4)\) were used for this set of observations. The preliminary processing of the images was done using the MIDAS package. We extract 115 echelle orders with absolute numbers between 56 and 170 which correspond to the wavelength region of 3350–10200 Å.

The crucial stage of the processing is the wavelength calibration. This issue is of special importance for spectral observations of stars with exoplanets, for which the Hamilton Spectrograph is actively used. The wavelength standard is calculated by means of a hollow-cathode lamp manufactured by S&J Juniper & Co. (Serial No. 531495). The lamp, designated LICK-HCL-002, presumably has a thorium cathode, a quartz envelope, and is filled with a mixture of argon (90%) and neon (10%). Several spectral lines of Ar were identified which launched the calibration with the MIDAS command IDEN/ECH using the standard line list for a ThAr lamp from the file than100.tbl. However, this procedure identified only \( \sim 5\% \) of all detected lines (63 lines from 1326) using the two-dimensional solution of the standard echelle relation, far below what is needed to perform accurate calibration. Moreover, only 36 of the 115 orders have identified lines. For independent calibration of each order in MIDAS, the number of identified lines \( \sim 18\% \), and the typical error of an automatic calibration is 0.1–0.7 Å. Only about 20 orders have an accuracy of about 0.01 Å, but most are located at a region of \( \lambda < 5000 \) Å where the signal-to-noise ratio is low. A similar situation has arisen in the case of the more detailed ThAr line list from NOAO (Willmarth et al. 2008). Thus, the automatic calibration is wrong due to the mismatch between the lamp spectrum and the ThAr line list. The calibration may also be done using only argon lines in manual mode. For this, we would need at least a few evenly distributed lines in each order but such information is available for only about a third of the orders, therefore making the calibration impossible.

Given this unexpected failure, we scrutinize the problem and come up with a solution which is the major subject of the present paper. We hope the results will be of interest for observers who face the need for wavelength calibration with this instrument. We substantially expand the line list of argon appropriate for the wavelength calibration thanks to a great number of titanium lines we identified in the lamp spectrum.

The contents of the paper are as follows. We first analyze the spectrum of the lamp LICK-HCL-002 and identify Ti i lines (Section 2). We then determine the gas temperature to compile the line list of Ti appropriate for the spectrum produced by the lamp (Section 3). In Section 4, we use the new line list to perform wavelength calibration of the Hamilton Spectrograph.

2. LAMP SPECTRUM IDENTIFICATION

The relative intensity of spectral lines in the spectra of hollow-cathode lamps generally depends on a number of factors including the current, voltage, density of filling gas, service time, and possibly some other factors as well. The direct outcome of this dependency is that one never finds exactly the same spectra for the arbitrary pair of lamps. Even so, one can always find a set of lines common to the spectra of different lamps. In Figure 1, we show the spectrum of the 110th echelle order compared with the spectrum of ThAr lamp obtained with the EMMI REMD echelle spectrograph installed on the ESO New Technology Telescope (NTT). This lamp was used previously, e.g., in Pakhomov et al. (2012). This order was selected because of the several strong thorium lines in this region. The calibration of the Lick spectrum was performed using only Ar i and Ar ii lines. The two spectra demonstrate apparent dissimilarities: only argon lines are common to both and numerous thorium lines are absent in the Lick spectrum. The inset of Figure 1 demonstrates...
Figure 1. Spectrum of the Lick lamp from the 110th order (bottom) and NTT spectrum of a ThAr lamp (top). The dotted line indicates commonly identified Ar lines. The inset shows a ten-fold intensity zoom of the Lick lamp spectrum with dashed lines emphasizing the absence of thorium lines.

Figure 2. Same as Figure 1 but for the 114th order.

this point in more detail. The Lick spectrum contains a huge number of strong, unidentified lines that are not observed in the NTT spectrum. In this regard, we should consider the possibility that the lamp cathode is made of material other than thorium.

In an attempt to resolve the issue of unknown spectral lines, we consider the 114th order (Figure 2), in which case we find five lines of Ar II to start the wavelength calibration and 15 unidentified lines with a relative intensity $>0.1$. The accuracy of the preliminary calibration is $\sigma \approx 0.002 \, \text{Å}$ using a polynomial approximation of the third order. Positions of all unidentified lines match neither thorium nor neon as in the case of the 110th order. Therefore, the unknown lines obviously belong to some other element. To define this element, we compiled two line lists from the VALD database (Kupka et al. 1999): the first contains lines that coincide with wavelengths of unknown lines with an accuracy of $\Delta \lambda = \pm 0.03 \, \text{Å}$ and the second with an accuracy of $\Delta \lambda = \pm 0.01 \, \text{Å}$. If the unknown lines belong to the same single element then it should occur at least 15 times in the list. In the case of two elements, the sum of the lines should be 15. When we reduce the accuracy from 0.03 to 0.01 Å, the required element or elements should remain in the list, while other elements should be separated. The first line list reveals 16 lines of Ti I and 10 lines of Fe II; for the rest of elements, the number of lines $<5$. The second list contains 14 lines of Ti I and 4 lines of Fe II; for other elements, the number of lines $<2$. Thus, titanium and iron are possible elements that form the unknown lines in the lamp spectrum.

First, we test iron because it can be used for the lamp cathode as well. In an astronomical practice, an FeAr lamp is used sometimes for wavelength calibration. For example, at the Terskol Observatory of the Institute of Astronomy of the Russian Academy of Sciences, wavelength calibration is performed with an FeAr lamp (Pakhomov et al. 2009). The line list for an FeAr lamp can be found in the MIDAS package. We checked the possibility that the unknown lines might belong to iron and ruled this out due to unsuccessful calibration using the FeAr list and absence of the strongest iron lines in the spectrum of the studied lamp.

We therefore turned to titanium as the likely source of the strong and weak lines seen in the 114th order (Table 1). The table contains the measured wavelength, laboratory wavelength

| $\lambda_{\text{meas}}$ (Å) | $\lambda_{\text{Ti}}$ (Å) | $\Delta \lambda$ (Å) | $E$ (eV) | $\log gf$ | $I_{\text{rel}}$ |
|--------------------------|--------------------------|---------------------|--------|---------|--------|
| 4981.727                 | 4981.731                 | 0.004               | 3.337  | 0.577   | 0.091  |
| 4991.063                 | 4991.065                 | 0.002               | 3.319  | 0.467   | 0.091  |
| 4997.093                 | 4997.096                 | 0.003               | 2.480  | −0.207  | 0.021  |
| 4999.499                 | 4999.503                 | 0.004               | 3.305  | 0.359   | 0.095  |
| 5007.206                 | 5007.210                 | 0.004               | 3.294  | 0.258   | 0.083  |
| 5014.203                 | 5014.276                 | 0.073               | 3.285  | 0.332   | 0.141  |
| 5016.158                 | 5016.161                 | 0.003               | 3.319  | −0.574  | 0.012  |
| 5020.023                 | 5020.026                 | 0.003               | 3.305  | −0.414  | 0.020  |
| 5022.864                 | 5022.868                 | 0.004               | 3.294  | −0.434  | 0.024  |
| 5024.843                 | 5024.844                 | 0.001               | 3.285  | −0.602  | 0.016  |
| 5035.902                 | 5035.903                 | 0.001               | 3.921  | 0.492   | 0.011  |
| 5036.463                 | 5036.464                 | 0.001               | 3.904  | 0.239   | 0.014  |
| 5038.397                 | 5038.397                 | 0.000               | 3.890  | 0.159   | 0.012  |
| 5039.957                 | 5039.957                 | 0.000               | 2.480  | −1.236  | 0.203  |
| 5064.644                 | 5064.653                 | 0.009               | 2.495  | −1.059  | 0.161  |
of Ti i, their difference, the energy of the upper level $E$, the oscillator strength $\log gf$, and the relative line intensity $I_{\text{rel}}$. The wavelength coincidence is remarkable with the exception of the 5014.276 Å line in which case $\Delta \lambda = 0.073$ Å. This line, however, is blended with another line of Ti i at $\lambda = 5014.187$ Å ($E = 2.472$ eV and $\log gf = -1.462$). It is noteworthy that all the identified Ti i lines have large transition probabilities and low excitation potentials, both properties that favor relatively high line intensity in accordance with the observed lamp spectrum. This rule holds for the other echelle orders as well. We therefore conclude that the Lick lamp cathode is made of titanium.

This conclusion seems rather unexpected given the fact that the lamp is designated as ThAr. On the other hand, hollow-cathode lamps with a Ti cathode are widely manufactured and normally used for spectral calibration in physics and chemistry. S&J Juniper & Co. also produces TiAr lamps (catalog number is 4163). We conjecture that a Ti cathode lamp got into a ThAr lamp shipment by mistake.

In astronomy, Ti cathode lamps are not used which explains why a Ti line list is absent in MIDAS and other packages designed for processing echelle spectra. Therefore, it is important to create a list of spectral lines of titanium in the optical range to use with this hollow-cathode lamp installed at the Hamilton Spectrograph.

### 3. TITANIUM LINE LIST

The line list of Ti i, which corresponds to observed spectral lines, can be retrieved from the VALD database. To this end, we have to estimate the temperature of the line-emitting gas. To this end, we use the Boltzmann level population

$$ F = \frac{gf}{\lambda^3} \exp\left(\frac{-E}{kT}\right), $$

where $g$ is the statistical weight of the upper level, $f$ is the oscillator strength for the transition, $E$ is the excitation energy of the upper level, $k$ is the Boltzmann constant, and $T$ is the excitation temperature.

In the logarithmic form we come to the linear dependence on the excitation potential (aka the Boltzmann plot)

$$ \log \left(\frac{gf}{\lambda^3}\right) = a + bE, \quad (1) $$

where $a$ is a constant that determines the absolute scale of oscillator strengths, and $b = 5040/T$ is a constant representing the decrement of a level population.

#### 3.1. Flux Calibration

The temperature, i.e., the constant $b$ of Equation (1), can be determined if one knows the line-calibrated intensities. To recover line intensities from the echelle spectra, one needs the blaze function and energy distribution for the echelle orders. This task was performed using the absolute calibration of the echelle spectrum of the B-star HR 1215 taken during the same observations. Since this star is not a spectrophotometric standard we recover its spectral energy distribution (SED) via the determination of the stellar effective temperature $T_{\text{eff}}$ and gravity log $g$. The LSR star velocity components ($U, V, W) = (18.9, -0.8, -4.8) \text{ km s}^{-1}$ are within the velocity dispersion of the thin disk in the solar neighborhood (Famaey et al. 2005). Therefore, we assume solar metallicity.

Parameters of the stellar atmosphere are estimated via a two-step procedure. First, using photometric data and calculating the preliminary SED we determine the initial blaze function of the echelle and extract the stellar spectrum. On the second step we fit the observed spectrum by the synthetic stellar spectrum and calculate the final blaze function.

**Step 1.** The preliminary values of $T_{\text{eff}}$ and reddening $E(B-V)$ are found from the two-color diagram ($U-B$) and ($B-V$). The observed color indices are $(B-V) = -0.03$ and $(U-B) = -0.74$ (cf. SIMBAD and Belyakina & Chugainov 1960). These colors, combined with the curve of the colors of normal stars, result in the reddening estimate $E(B-V) = 0.20$ mag. The dereddened color is then $(B-V)_{0} = -0.23$ which corresponds to the effective temperature $T_{\text{eff}} \approx 24,000$ K.

The gravity is estimated using the standard relation:

$$ \log g = -10.607 + \log(M/M_{\odot}) + 4 \log T_{\text{eff}} - 0.4(4.69 - V - 5 - 5 \log \pi - A_{V} - BC), $$

where $M/M_{\odot}$ is the stellar mass in solar units, $V = 5.49$ mag and $A_{V} = 3.1E(B-V)$ are magnitude and absorption in the $V$-band, $BC$ is the bolometric correction, and $\pi = 3.76 \pm 0.35$ is the Hipparcos parallax (van Leeuwen 2007). With the mass $M = 9 \pm 1 M_{\odot}$ estimated from evolutionary tracks (Schaller et al. 1992) one obtains $\log g = 4.0 \pm 0.1$. With the derived values of $\log g$ and $T_{\text{eff}}$ we calculate the synthetic spectrum model using the ATLAS9 code (Kurucz 1993).

#### 3.2. Excitation Temperature of Ti i

The observed lamp spectrum of Ti i is reduced using the final blaze function to produce the spectrum in relative intensities. All the observed lines of Ti i in the whole spectral range have been identified using the VALD database. Their relative intensities are used to infer temperature from the Boltzmann plot (Figure 4). A typical error in $\log(gf/\lambda^3)$ is about 0.2–0.5 dex; the uncertainty originates from the spectrum noise, errors of the blaze function, and errors of oscillator strengths. The error is larger for weak lines, i.e., for larger $E$. From the linear least-squares fit we obtain $a = 17.82 \pm 0.25$ and $b = 1.582 \pm 0.076$ (Equation (1)); the latter suggests an excitation temperature of $5040/b = 3200 \pm 150$ K.
Johnson blended lines with a separation less than 0.1 Å. The final list of R lines in our line list. The blending effect all the Ti F > F\textsubscript{min} indicates a rather high ionization fraction of Ti ii of the observable spectrum. Using measured intensities of Ti \textit{ii} lines and assuming the Boltzmann level population we derive the number ratio of ions N(Ti \textit{ii})/N(Ti \textit{i}) \approx 0.25, which indicates a rather high ionization fraction of Ti \textit{ii} \sim 0.2. Ti \textit{ii} is represented by 14 lines in our line list. The blending effect is not taken into account in the final list of Ti \textit{i} and Ti \textit{ii} lines. For the resolving power R = 60,000 the line list contains 28 blended lines with a separation less than 0.1 Å. The final list of titanium lines is presented in Table 2, where the first column is the wavelength, the second column is the calculated relative intensity, and the last column is the titanium ion.

4. WAVELENGTH CALIBRATION OF THE HAMILTON SPECTROGRAPH

The TiAr spectrum taken on the Hamilton Spectrograph is calibrated using the line list produced by merging the Ti \textit{i} and Ti \textit{ii} line list with the Ar line list from NOAO (Willmarth et al. 2008). The first extracted order (absolute number is 170) and the last order (absolute number is 56) have spectral ranges of 3315.71–3402.41 Å and 10063.24–10326.02 Å, respectively. Wavelength residuals of the calibration are plotted in Figure 5. The average deviation is \( \Delta \lambda \approx 0.006 \) Å. The accuracy is less than 0.01 Å for orders above 90 \( (\lambda \lesssim 6500) \), while in the red the average accuracy is about 0.01 Å. The accuracy deteriorates toward the red region because the strong Ar lines produce light pollution on the CCD, and because the red part contains too few reference lines. In this region the calibration was made by solving the standard echelle grating equation.

Table 2

| Wavelength (Å) | \( I_{\text{rel}} \) | Ion |
|----------------|----------------------|-----|
| 3000.865       | 20.4                 | Ti \textit{i} |
| 3002.725       | 1.4                  | Ti \textit{i} |
| 3042.540       | 1.7                  | Ti \textit{i} |
| 3088.025       | 715.2                | Ti \textit{ii} |
| 3100.663       | 1.3                  | Ti \textit{i} |
| 3119.723       | 5.0                  | Ti \textit{i} |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

5. SUMMARY

In this study we show that in the spectrum of a hollow-cathode “TiAr” lamp, thorium lines are absent, whereas numerous unknown spectral lines are present. Due to this fact, the calibration of the Hamilton Spectrograph in all echelle orders was nearly impossible. To solve this problem we state that the unknown lines are actually titanium lines. We estimate the temperature of gas in the lamp, and create the theoretical list.
of the relevant Ti i and Ti ii lines that should be observed in the spectra. Using this line list compiled with a list of argon lines, the calibration of the Hamilton Spectrograph was done with an accuracy better than 0.01 Å.

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Facility: Shane (Hamilton Spectrograph)

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