Extracting the Physical Parameters of a Sample of M-dwarfs from High-resolution Near-infrared Spectra

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Abstract. This study is part of an effort to determine the physical and kinematical properties of a sample of 36 nearby late M-dwarfs, with spectral types M5-M9.5. They are the targets of a program to search for exoplanets orbiting around them from the radial velocity method using the near-infrared echelle spectrograph NIRSPEC on the Keck II telescope. Preliminary results about the effective temperature, surface gravity, and rotational broadening of a subsample of nine M-dwarfs are presented. The analysis is based on the comparison of the spectra obtained in the J-band with a high resolving power of 22,000 and stellar atmosphere synthetic models using the PHOENIX and the PHOENIX/DRIFT codes. This study shows that the strong potassium absorption doublet at 12432 and 12522 Å is useful to determine the effective temperature. Our results are of interest for the new generation of near-infrared spectrographs that are being developed to measure radial velocities with unprecedented precisions of a few ms⁻¹, for which accurate theoretical models for comparison are needed.

1. Introduction

M-dwarfs represent the most numerous stellar population in the Milky Way (van de Kamp 1971). Models of their atmospheres have been developed for quite some time (Auman 1969; Mould 1975). It has been recognized that the main sources of blanketing effects on M-dwarfs are the H₂O and TiO molecules. TiO absorption bands start to weaken at the latest M spectral types and eventually disappear in the L dwarfs (Mar-
This effect is best explained by condensation of dust grains in the atmospheres of ultracool dwarfs (Tsuji et al. 1996).

In the spectral type range M5-M9.5, most stars are expected to be very low-mass cool dwarfs, although some of them could be young brown dwarfs. In fact, in the well-studied Pleiades cluster, the transition between stars and brown dwarfs occurs at a spectral type of M6.5 (Martin et al. 1996). It has been estimated that the substellar-mass boundary is located at M9 for an age of 1 Gyr (Magazzu et al. 1998). Determination of the surface gravity in late-M dwarfs can yield constraints on their age and mass, and hence on their stellar or substellar status. An early attempt to perform this type of analysis was carried out by Zapatero Osorio et al. (2004) for the very low-mass binary GJ569 Bab.

The comparison of high-resolution near-infrared (NIR) spectroscopy with stellar atmosphere models is a powerful tool to extract the kinematical and physical properties of cool dwarfs. It has been used, e.g., to characterize T-dwarfs (Del Burgo et al. 2009).

This study is aimed at studying a sample of M-dwarfs from high-resolution NIR spectra and stellar atmosphere models. Sect. 2 presents the radial velocity (RV) survey for which this work is performed. Sect. 3 shows a summary about the observations, processing and preparation of the data, as well as the description of the models. In Sect. 4 the results and discussion about the extracted properties of the sample are presented.

2. The Radial Velocity Survey

This work is part of a project to perform a RV survey of cool dwarfs that may host planets. The project was granted Keck NASA observing time in 2007 to obtain high-resolution spectroscopy in the $J$-band over a period of 1 year of 36 nearby M-dwarfs (distance $< 20$ pc) using NIRSPEC (McLean et al. 1998) on the Keck II telescope in Hawaii (USA). These M-dwarfs are not known to be binaries and have spectral types ranging from M5 to M9.5. The achieved RV precisions between 100 ms$^{-1}$ and 400 ms$^{-1}$ permits the detection of exoplanets with 2-8 Jupiter masses at 1 AU or 0.7-2.8 Jupiter masses at 0.1 AU (Rodler et al. 2012). The ultimate goal of this RV project is to discover habitable rocky planets around cool dwarfs. This is the main science driver of the new generation of NIR spectrographs aimed at measuring RVs with unprecedented precision (see, e.g., project CARMENES: Quirrenbach et al. 2010).

3. Observations, Data Processing, Synthetic Models, and Data Preparation

3.1. Observations and Data Processing

A sample of 36 M-dwarfs, with 7.09 $< J <$ 13.24, were observed with the NIR echelle spectrograph NIRSPEC/Keck II. The observing dates were 2007 April 30th, June 24th, 25th, October 25th, 26th, and December 23rd, 24th. The instrumental setup was fixed to get ten echelle orders in the $J$-band, from 1.148 to 1.346 $\mu$m. The nominal dispersion varies from 0.164 A pix$^{-1}$ (at blue wavelengths) to 0.191 A pix$^{-1}$ (at red wavelengths), and the final resolution element is 0.55 – 0.70 A pix$^{-1}$ at 1.2485 $\mu$m, i.e., about the central wavelength, corresponding to a resolving power $R \approx 22,000$. A detailed description of the applied data processing can be found in Zapatero Osorio et al. (2006).
3.2. Description of the Atmosphere Models

Two distinct stellar atmosphere synthetic models, each usable for a different effective temperature ($T_{\text{eff}}$) range, have been used. The general-purpose stellar atmosphere PHOENIX code (Hauschildt & Baron 1999), in particular version v16, is used for $T_{\text{eff}} \geq 3000$ K. Version v16 includes a number of improvements compared to previous versions, such as a complete new equation of state for ions, molecules, and condensation, updated opacity databases, and improved line profiles for atomic lines. For $T_{\text{eff}} < 3000$ K the Drift-PHOENIX code, which is a merger of the PHOENIX code and the dust model Drift (Helling et al. 2008), is used. The dust grains are composites and yield improved opacities in contrast to the grains in earlier models, and the use of a non-phase-equilibrium chemistry avoids an overestimated condensation/evaporation.

3.3. Data Preparation

The synthetic models used for this analysis have $1500 \leq T_{\text{eff}} \leq 3500$ K (steps of 100 K) and $3.5 \leq \log g \leq 5.5$ (steps of 0.5 dex) (cgs). The models were modified in order to match the observing set-up of the NIRSPEC observations and make possible their comparison. First, the theoretical models were transformed to take into account the projected rotational velocity ($v_{\text{rot}}$) of the dwarfs using the formalism of Gray (1992). A range of values between $0 \leq v_{\text{rot}} \sin i \leq 100$ km s$^{-1}$ (steps of 1 km s$^{-1}$) was introduced. Second, the models were convolved with a Gaussian that mimics the instrumental profile along the dispersion axis. Third, the resulting models were rebinned to the same resolution of the observations. Finally, models and observed spectra are normalized.

All of our observed spectra were moved to vacuum wavelengths (i.e., laboratory frame of reference) for a proper comparison with the grid of models. A cross-correlation of the observed spectra with each model is performed. This provides a determination of the RV (not presented here). In order to constrain the number of possible solutions (in the parameter space of $v_{\text{rad}}$, $v_{\text{rot}} \sin i$, $T_{\text{eff}}$, and $\log g$) provided by our large set of models, the root-mean-squares (RMS) of the differences between observed spectra and models are obtained. For each object, the best model is that for which RMS is minimum. For a more detailed description of the method see Del Burgo et al. (2009).

4. Results and Discussion

Table 1 shows the extracted values of $v_{\text{rot}} \sin i$, $T_{\text{eff}}$, $\log g$, and the RMS of the best model for the selected nine M-dwarfs. The spectral type (SpT) and $J$ magnitude of each star is also indicated. The uncertainties are half of the steps used to create the grid. For $v_{\text{rot}} \sin i$, it should be noted that the resolution element is $\sim 28$ km s$^{-1}$. In Del Burgo et al. (2011), using a sample of 11 M-dwarfs of the same NIRSPEC program (4 of which are included in this analysis) also found low values for some (e.g., GJ1002, GJ406 or VB10) object, all consistent with those published in the literature. A more detailed analysis will be presented in del Burgo et al. (in prep.).

Conversely to Del Burgo et al. (2011) who have averaged the extracted values corresponding to $v_{\text{rot}} \sin i$, $T_{\text{eff}}$ and $\log g$ for all the echelle orders, here it is only used the order in the wavelength range $12400 - 12580$ Å, which includes the strong absorption doublet at 12432 and 12522 Å (see example in Fig.1). This order is particularly useful to determine $T_{\text{eff}}$. For the 4 dwarfs in common with Del Burgo et al. (2011) we found very similar values of $T_{\text{eff}}$ for the two stars with the earliest spectral types (LP860-41,
del Burgo et al.

Figure 1. Spectrum of 2MASS0045753-1709369 (M5.5) for the echelle order with potassium absorption doublet at 12432 and 12522 Å. Thick and thin lines stand for the observed spectrum and best theoretical model, respectively.

Table 1. Properties of M-dwarfs derived from the echelle order with KI lines at 12432 and 12522 Å.

<table>
<thead>
<tr>
<th>Object</th>
<th>Sp. type</th>
<th>J mag</th>
<th>$v_{\text{rot}} \sin i$ [km s$^{-1}$]</th>
<th>$T_{\text{eff}}$ [K]</th>
<th>log g</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GJ1156</td>
<td>M5.0</td>
<td>8.52</td>
<td>21</td>
<td>3000</td>
<td>5.5</td>
<td>0.025</td>
</tr>
<tr>
<td>2MASS J00045753-1709369</td>
<td>M5.5</td>
<td>10.99</td>
<td>35</td>
<td>3000</td>
<td>5.5</td>
<td>0.031</td>
</tr>
<tr>
<td>LP860-41</td>
<td>M6.0</td>
<td>10.26</td>
<td>26</td>
<td>2400</td>
<td>4.5</td>
<td>0.037</td>
</tr>
<tr>
<td>2MASS J03542008-1437388</td>
<td>M6.5</td>
<td>11.34</td>
<td>35</td>
<td>2300</td>
<td>4.5</td>
<td>0.044</td>
</tr>
<tr>
<td>LHS1937</td>
<td>M7.0</td>
<td>12.01</td>
<td>18</td>
<td>2500</td>
<td>5.0</td>
<td>0.060</td>
</tr>
<tr>
<td>2MASS J15460540+3749458</td>
<td>M7.5</td>
<td>12.44</td>
<td>22</td>
<td>2500</td>
<td>5.0</td>
<td>0.063</td>
</tr>
<tr>
<td>LP349-25</td>
<td>M8.0</td>
<td>10.61</td>
<td>70</td>
<td>2300</td>
<td>4.5</td>
<td>0.031</td>
</tr>
<tr>
<td>2MASS J18353790+3259545</td>
<td>M8.5</td>
<td>10.27</td>
<td>58</td>
<td>2300</td>
<td>5.0</td>
<td>0.064</td>
</tr>
<tr>
<td>2MASS J1733189+463359</td>
<td>M9.5</td>
<td>13.24</td>
<td>30</td>
<td>2100</td>
<td>4.5</td>
<td>0.080</td>
</tr>
</tbody>
</table>

LHS1937). For those with the latest spectral types (LP349-25, 2MASSJ1733) we found higher values of $T_{\text{eff}}$. Although the differences are within the errors, these results are because all echelle orders apart from that with the strong absorption doublet at 12432 and 12522 Å are not so sensitive to $T_{\text{eff}}$.

The synthetic models reproduce the haze of absorption features, which is particularly significant in the reddest echelle order (13270 – 13460 Å), with abundant water vapor, although the strength of a number of faint features is not so well matched. This is partly due to the line modeling, but also to problems in the flat-fielding and the sub-
traction of some telluric lines. We have recently investigated alternative techniques to improve the telluric subtraction (Rodler et al. 2012).

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