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NEAR-INFRARED INTEGRAL FIELD SPECTROSCOPY OF YOUNG LATE-M AND EARLY-L DWARFS CLOSE TO THE DEUTERIUM-BURNING BOUNDARY

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Abstract. We report the first results of a uniform high-quality spectral characterization of 8 young late-M and early-L dwarfs in the near-infrared (1.1-2.45 μm) with the integral field medium-resolution (R=1500-2000) spectrograph SINFONI. Our targets are companions to stars, or free-floating objects members of young (< 100 Myrs) associations. The sample noticeably includes the companion to AB Pic, which is known to lie at the deuterium-burning boundary (13.6 M_{Jup}). A comparison of the spectrum of AB Pic b with empirical libraries of young late dwarfs spectral standards and to synthetic atmosphere spectra yielded the spectral type, the surface gravities (*log*(g)) and the effective temperature (T_{eff}) of the source. By combining T_{eff}, *log*(g), the observed photometry, the surface fluxes from atmosphere models and the known distance of AB Pic A, we derived new masses, luminosities and radii estimates that were carefully compared to evolutionary models predictions.

1 Introduction

Since the discovery of the first brown dwarfs (BD) companions to GD165 B (Becklin & Zuckerman 1988), and Gl 229 B (Nakajima et al. 1995), more than 600 low-mass stars and BDs (also named ultracool dwarfs) have been discovered, isolated in the field, or as companion to stars. The spectra of many of these sources (Geballe et al. 2002; McLean et al. 2003, Cushing et al. 2005) revealed a mélange of narrow atomic features and broad absorptions produced by molecules and condensates from refractory elements. Two new spectral classes *"L"* and *"T"* were then added to distinguish these objects from "normal" M dwarfs. A spectral classification scheme is now well establish at visible and near-infrared wavelengths (see the review of Kirkpatrick 2005).

The observational programs to find substellar objects (M < 0.078 M_{Jup}) members of young nearby associations and in star forming regions brought a new sample of young very low mass objects. They are companions to stars, free-floating objects, or binaries with masses close or below the deuterium-burning boundary (M < 13.6 M_{Jup}, currently used to distinguish planets from brown dwarfs). The great diversity of these systems rises questions on their formation mechanisms.

Our knowledge of their chemical and physical properties is currently very limited and even inexistent for young T dwarfs. Their larger radii (still contracting) and very lower masses than their same spectral type counterparts in the field made them less dense. Together with the effective temperature (T_{eff}), the surface gravity *log*(g) plays an important role, modifying the pressure and the composition of cloudy emissions layers. In the near-infrared (NIR), spectra of young M and of the known early-L dwarfs show a weakening of alkali lines and the appearance of a triangular-shape in the H band (McGovern et al. 2004; Kirkpatrick et al. 2006, hereafter K06). So far, only one study aimed at characterizing the impact of surface gravity on their spectral classification (Lodieu et al. 2008).

We present the first results of a uniform high-quality spectral characterization of late-M and early-L dwarfs in the NIR (1.1-2.45 μm) with the integral field medium-resolution (R=1500-2000) spectrograph SINFONI. Our spectral library is described in Sec. 2. We then focus on the study of the young very low mass companion AB Pic b in Sec. 3.

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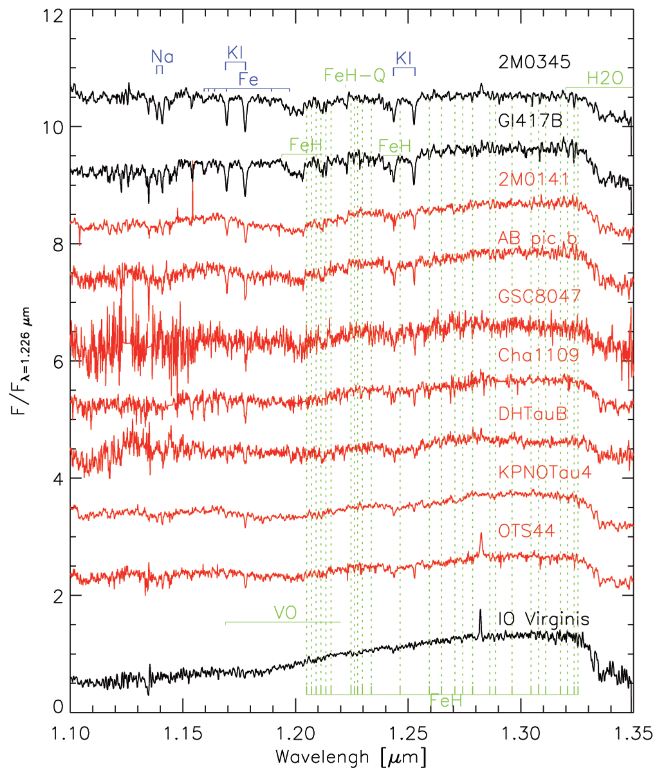

Fig. 1. The SINFONI J-band normalized spectra of our sources. Spectra of young sources are plotted in red. The spectra of the L0 dwarf 2M0345, the L4 companion Gl 417 B (black line) and of the M giant IO Virginis are reported in black for comparison. Molecular lines are flagged in green. Atomic lines are identified in blue. The young M and L dwarfs spectra appear intermediate between those of field dwarfs and of the giant.

2 The library

2.1 Observations and source sample

Our sample is composed of 8 ultracool dwarfs with estimated spectral types ranging from M8 and L0. It includes the companions to TWA5 A, AB Pic, GSC 8047-0232, DH Tau and to the young field dwarf star Gl417. Because of the limited number of young late-M and early-L companions, we also observed the isolated objects KPNO Tau 4, OTS44 and Cha1109-7734. TWA5 B, AB Pic and GSC 8047-0232 are members of the young (age 8–40 Myrs) nearby associations TW Hydrae and Tucana-Horologium. DH Tau and KPNO Tau are associated with the Taurus (age∼1–2 Myrs) molecular cloud. OTS44 and Cha1109-7734 belong to the Chameleon molecular cloud (age∼2 Myrs). Finally, the L0 field dwarf 2MASS J03454316+2540233 (hereafter 2M0345) and the late M giant IO Virginis were also observed. They serve as reference for high and very low surface gravity object spectra.

Our sources were observed with the integral field NIR (1.1–2.45 μm) spectrometer SINFONI (Eisenhauer et al. 2003; Bonnet et al. 2004), installed on the Very Large Telescope UT4 (Yepun). The instrument benefits from the high angular resolution provided by a modified version of the Multi-Applications Curvature Adaptive Optic (AO) system MACAO and of the integral field spectroscopy offered by SPIFFI (SPectrograph for Infrared Faint Field Imaging). All the sources were observed with the J (1.1–1.4 μm) and $H+K$ (1.45–2.45 μm) gratings at resolving powers of 2000 and 1500 respectively. The adaptive optics system was used for TWA5B, GSC8047-0232 B, AB Pic B and DH Tau B to limit the contamination of their primary star in the field of view of the instrument.

2.2 Data reduction

The reduction of SINFONI data is a long and complex task. We used the SINFONI data reduction pipeline (Modigliani et al. 2007) and custom *IDL* routines. Our routines correct raw images from negatives rows created during the bias subtraction (see *The ESO data reduction cookbook*; version 1.0, ESO, 2007) and from correlated noises that affect a part of the dataset. The pipeline then carries out the flagging of hot and non-linear pixels, the distortion, and the wavelength calibration of the detector. When a sky frame had been acquired, it is subtracted to the object frame. Otherwise, the sky is estimated from the median of a series of dithered exposures and subtracted to the object frame. The resulting frame is then flat fielded and corrected from bad pixels and distortions. Datacubes are finally reconstructed and are merged into a master cube. A telluric standard star observed the same night is used to correct the spectra from telluric absorption lines.

2.3 Preliminar spectral analysis

The SINFONI J-band normalized spectra are presented in Fig 1. Young sources spectra show atomic and molecular features intermediate between those of the L0 dwarf 2M0345 and of the M giant IO Virginis. The reduced K I absorption depth at 1.169 μm, 1.177 μm, 1.243 μm and 1.253 μm, together with the reduced FeH absorption at 1.2 μm, are characteristic of intermediate surface gravity objects. In the H band, our spectra present a triangular shape typical of young M and L dwarfs (K06). Finally, our K band spectra present CO overtones longward 2.9 μm. In the following section, we present a complete spectral analysis of the AB Pic b companion.

3 The case of AB Pic b

AB Pic b was detected by Chauvin et al. 2005 at 5.5” from the young (~30 Myrs) K2V star AB Pic A. Evolutionary models predict a companion mass of 13–14 M_{Jup} in agreement with the L0–L3 spectral type derived from NACO K-band spectroscopy. Additional SINFONI spectra with SNR ranging from 40 in the J band to 50 in the H+K band were necessary to complete its characterization.

3.1 A new spectral type determination

Our spectra were normalized and compared to young M8–L4 spectral standards (Lodieu et al. 2008, Lafrenière et al. 2008) members of Upper Sco (~5 Myrs). A χ^2 minimization was obtained for young L1 and L2 dwarfs in the J band, L0 dwarf in the H band and, L0 and L2 dwarfs in the K band. L2 and L4 were excluded from the visual comparison in the H band. We confirmed this preliminary spectral type determination using spectral indexes designed to measure the depth of water absorptions at 1.34 μm, 1.5 μm, and 2.04 μm (Allers et al. 2007; Slesnick et al. 2004). Finally, the good match of our J-band spectrum with that of the young isolated dwarf 2MASS J01415823-4633574 (see Fig. 1) classified as L0 in the optical (K06) confirms that AB Pic b is a L0–L1 dwarf.

3.2 Effective temperature and surface gravity

We compared our spectra to models generated spectra of the AMES–Dusty00 library (Allard et al. 2001). AMES–Dusty00 incorporates formation of dust in the atmosphere below 2600 K. During the comparison, we masked H_2O absorptions from 1.32 to 1.60 μm and from 1.75 to 2.20 μm that are known to be overestimated in the models (see K06).

The J band was fitted for $T_{\rm eff} = 2000 \pm 100$ K and $\log(g) = 4.0 \pm 0.5$ dex. The fit was still visually acceptable for $T_{\rm eff}$ down to 1700 K and up to 2100 K. The observed depth of CO overtones at $\lambda \geqslant 2.3\mu$m and the shape of the pseudo-continuum in the K-band are better reproduced at $T_{\rm eff} = 2500$ K. However, this band is dominated by H_2O absorptions. A better match is achieved at $T_{\rm eff} = 2000$ K and $\log(g) = 4.0$ dex using the most recent SETTL08 library (D. Homeier, Priv. com.).

In conclusion, both AMES–Dusty00 and SETTL08 libraries yield $T_{eff} = 2000^{+100}_{-300}$ K and $\log(g) = 4.0 \pm 0.5$ dex for AB Pic b.

3.3 Mass estimations

We infer a mass of 11 $M_{\rm Jup} \leq M \leq 14 M_{\rm Jup}$ from the estimated $T_{\rm eff}$ of part 3.2 and evolutionary tracks (Chabrier et al. 2000). However, tracks remain to be calibrated at young ages and very low masses down to the planetary mass regime where the formation mechanisms could actually play a key role (Marley et al. 2007). We then tried to use alternative methods to estimate the mass of AB Pic b.

Using the empirical relations between BC_K and spectral types for *field dwarfs*, we derived a bolometric correction $BC_K = 3.24^{+0.18}_{-0.19}$ mag and a luminosity of -3.7 ± 0.2 $L/L_\odot$ for our source. Combining the luminosity with the T_{eff} and the *log(g)* derived in part 3.2, we estimate a radius of $1.22^{+0.70}_{-0.25}$ R_{Jup} and the mass of 1 to 45 M_{Jup} in agreement with evolutionary model predictions. However, the assumption of a similar BC_K-SpT relation between young and field dwarfs has never been established. It could therefore add systematic errors that are difficult to quantify.

A second alternative approach described by Mohanty et al. 2004, use the photometry and the surface fluxes provided by atmospheric models to estimate the mass of the companion. The absolute K-band magnitude is combined to the surface flux of the AMES–Dusty00 spectra at $T_{\rm eff} = 2000$ K and $\log(g) = 4.0$ to determine a radius of $0.81^{+0.83}_{-0.2}$ R_{Jup}. From the radius and the log(g), we deduce a mass of 2 to 24 M_{Jup}. Finally, the $T_{\rm eff}$ and the radius allows a new determination of the luminosity ($-3.72^{+0.15}_{-0.20}$ $L/L_{\odot}$). Using J-band fluxes leads to slightly different values. This was explained by a non-simultaneous reproducibility of the J and K_s-band surface fluxes at $T_{\rm eff} = 2000$ K. In both case, estimated masses of AB Pic b are still in agreement with evolutionary model predictions within uncertainties. Similar results are derived from the SETTL08 surface fluxes. However, one could note that these results strongly rely on the ability of atmospheric models to reproduce the *absolute* NIR fluxes of young L dwarfs.

4 Conclusions

We presented the first results of a program to build a library of near-infrared (1.1–2.5 μm) spectra of young late-M and early L dwarfs using the integral field spectrograph SINFONI. A preliminary analysis already confirmed the youth of our sources. AB Pic b is confirmed to be a L0–L1 dwarf. The comparison of its spectra to synthetic spectral grids enabled the estimation of $T_{eff} = 2000^{+100}_{-300}$ K and $\log(g) = 4.0 \pm 0.5$ dex. Our analysis highlights the difficulties of the models to successfully match the near-infrared spectra of young L dwarfs. We used two methods to derive masses estimations independent from evolutionary models predictions non-calibrated at young ages. They both confirm the predicted mass. However, even if they have been used in the literature (see Mohanty et al. 2004; Luhman et al. 2006; Seifahrt et al 2007) for young late M dwarfs, they could introduce systematic errors difficult to quantify. To solve the problem, simultaneous visible and infrared spectro-photometry of luminous young dwarfs could enable the direct determination of empirical luminosities and masses.

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