X-Shooter Medium Resolution Brown Dwarfs Library

E. Manjavacas[1], B. Goldman[1], J. M. Alcalá[1], M. Bonnefoy[1], F. Allard[1], R. L. Smart[1], V. Béjar[1], M. R. Zapatero-Osorio[1], T. Henning[1], H. Bouy[1]

[1]*Max Planck Institute für Astronomie, Königstuhl, 17, D-69117 Heidelberg, Germany*

Abstract. We obtain medium-resolution spectra in the optical (550-1000 nm, R∼5400) and the near-infrared (1000-2500 nm, R∼3300) using the *Wideband ultraviolet-infrared single target spectrograph* (X-Shooter) at the Very Large Telescope (VLT). Our sample is compound of 22 brown dwarfs binary candidates with spectral types between L1 and T7. We aim to empirically confirm or refute the binarity of our candidates, comparing them to spectral templates and to other brown dwarfs in a color-magnitude diagram, for targets that have published parallaxes. We use X-shooter at the VLT to obtain medium resolution spectra of the targets. We develop a slightly different analysis depending of the type of binaries we search for. To find L plus T brown dwarf binaries candidates, we comput spectral indices to select L-brown dwarfs plus T-brown dwarf binaries, and then we compare them to single and composite template spectra. To find potential L plus L or T plus T brown dwarf binaries, we first simulate their spectra creating synthetic binaries using combination of single template spectra. Then we compare them to our set of spectral libraries and composite of them to test if our method is able to find these binaries. Using spectral indices, we select four possible candidates to be combination of L plus T brown dwarfs: SIMP 01365662+0933473, 2MASSI J0423485-041403 (T0, known binary), DENIS-P J0255.0-4700 and 2MASS J13411160-3052505. We compare these candidates to single brown dwarf template spectra and combinations of them, and we select the best matches. All candidates beside SIMP 01365662+0933473 have decent matches to composite of two single template spectra. DENIS-P J0255.0-4700 have also good agreements to several late L and early T single template spectra. To find L plus L or T plus T brown dwarfs candidates, test the comparison to templates method use before to find L plus T brown dwarf binaries. The test consist on finding synthetic L plus L and T plus T binaries by comparing with spectral templates. We conclude that we cannot find L plus L and T plus T binaries using comparing to single and composite spectral templates, because the main difference between different L or T spectral types is just the spectral energy distribution. Optical and near infrared

spectra report in this paper will serve as templates for future studies in any of these wavelengths. In the near future, Gaia satellite will release high precision parallaxes of more than one billion of objects in the Milky Way, including hundred of brown dwarfs. These parallaxes will allow us to detect the overluminosity of brown dwarf binaries.

1. Introduction

Stars are social celestial bodies. They are normally born in nurseries of several entities. After childhood they leave their birth place and settle on the main sequency. A majority of stars remain in couples or hierarchical systems. Multiplicity has long been used as a powerful constrain on the star formation process, and they provide contrains in fundamental parameters, such of dynamical masses, essential to test atmospheric models. It is well known that the binary fraction decreases when decreasing mass. This fraction decreases from 80%-60% for O, A, B and G, K stars to 40% for the M dwarfs (Burgasser et al. 2007; Goldman et al. 2008).

The decreasing trend for binarity seems to be prolonged to the substellar regime. Martín et al. (1998), Reid et al. (2001), Gizis et al. (2003), Burgasser et al. (2003), Bouy et al. (2003), Koerner et al. (1999), Close et al. (2003), Burgasser et al. (2007), Luhman et al. (2007) and Goldman et al. (2008) estimate the fraction of binarity of about 20% for L and T brown dwarfs.

Allen et al. (2007) determined that 98% of the brown dwarfs have separations smaller as 20 AU. The peak of the separation distribution of brown dwarfs is $\sim$ 3 UA, which is very close to the resolution limit of the high resolution imaging surveys, as Burgasser et al. (2007) pointed out. Joergens (2008) searched for low-mass stars and brown dwarfs binaries in Chameleon using the radial velocity method, and concluded that the percentage of brown dwarfs binary systems with separations below 1 AU are less than $\sim$10%. Blake et al. (2010) determined that the binary frequency of very tight systems is $2.5^{+8.6}_{-1.6}$%. The fraction of very wide systems, i.e. systems with separations higher than 100 AU, was estimated by Burgasser et al. (2007) and Kraus & Hillenbrand (2012) among others, to be quite small $\sim$ 1%.

Mass is the parameter that determines the evolution of an object. As brown dwarfs do not burn hidrogen due to their low masses, age for objects is difficult to estimate. Monitoring binary systems orbits we are able to measure the dynamical masses empirically. Since the discovery of brown dwarfs, there have been several programs aiming to derive dynamical masses (Basri & Martín 1999; Bouy et al. 2004; Liu et al. 2008; Dupuy et al. 2009, 2010; Konopacky et al. 2010; Dupuy & Liu 2012). These programs provide feedback to constrain fundamental parameters of their components, such as age, mass, radius, temperature, etc. and test evolutionary and atmospheric models.

Atmospheric models allow us to disentangle the effect of varying T_{eff}, log g, and (metallicity) M/H on the spectral features. Below $T_{eff} \sim 2600$ K, models predict that clouds of iron and silicate grains begin to form, changing the opacity (Lunine et al. 1986, Tsuji et al. 1996, Burrows & Sharp 1999, Lodders 1999, Marley 2000, Marley & Ackerman 2001, Allard et al. 2001).

Allen et al. (2007) estimated that a fraction of $\sim$ 6-7% of brown dwarf binary systems have not been detected yet, as a consequence of observational biased. In this paper, we aim to find tight brown dwarf binary systems among a sample of 24 objects which were found to have different spectral classification in the optical and in the near-infrared or peculiar spectra in comparison with objects of the same spectral type. We intent to contribute to the improvement of the brown dwarf binaries stadistics, classify our objects in the optical and in the near-infrared as the same time.

2. Sample selection

We selected a sample of 24 brown dwarfs found in the literature with optical spectral types between L2 and T7, which have discrepant optical and near-infrared classification or peculiar spectra. Some of those unresolved binaries can probably already be guessed from this discrepancy, based on the optical or near-infrared schemes. Furthermore, we added some know brown dwarfs binary systems, LHS 102B (L4.5) and SDSS J042348.56-041403.4 (T0) [hereafter SD0423] to calibrate the results and confirm the reliability of our analysis. Two of our objects had noisy spectra, so we decided not to use them for our analysis. Therefore, we finally count with a sample of 22 optical and near-infrared spectra. Our list of candidates and their physical properties reported in the literature and their references can be found in Table .1.

3. Observations and data reduction

Our targets were observed using X-Shooter (Wideband ultraviolet-infrared single target spectrograph) on the Very Large Telescope (VLT) beteween October 2009 and June 2010, under programs 084.C-1092(A), 085.C-1062(A) and 085.C-1062(A). X-Shooter covers a range between 300-2500 nm. The instrument is separated into three arms: UVB (300-550 nm), optical (550-1000 nm) and near-infrared (1000-2500 nm). It was operated in echelle slit nod mode, using the 1.6" slit for the UVB arm, and the 1.5" for the optical and the near-infrared arms. This setup provides resolutions of ~3300 in the UVB and NIR, and ~5400 in the VIS. We moved the object along the slit between two positions following an ABBA pattern. Flux detected in the UVB arm is extremly weak, so that we do not use spectra taken in this range. Telluric standards are observed before or after every target at the same airmass. Bias, darks and flats are taken at the beginning of every night. Arc frames are taken every second day.

The spectra were reduced using the ESO X-Shooter pipeline in version 1.3.7. In the reduction cascade, the pipeline delete the non-linear pixels and subtracts bias in the optical or dark frames in the near-infrared. It generates the guess order from a format-check frame, a reference list of arc line and a reference spectral format table. It refines the order guess table into an order table from an order definition frame obtained by illuminating the X-Shooter pinhole with a continuum lamp. The master flat frame and the order tables tracing the flat edges are created. Finally, the pipeline determines the instrumental response and science data are reduced in slit nodding mode. In the case of the data taken in the near infrared, the pipeline did not product a satisfactory response function. In these case, we utilized the telluric star of the corresponding to every science target in that night to obtain the response function. We use the non-response calibrated spectrum of the target and the non-response calibrated spectra of the telluric star. We remove cosmetics and cosmics from the telluric stars, as well as the H and He absortion lines, using a Legendre polynomial

Table .1: List of observed targets. Magnitudes are given in 2MASS system.

Name	d_{trig} (pc)	SpT OPT	SpT NIR	Remarks
LHS 102B	13.2±0.7	L5	L4.5	Binary
2MASS J00361617+1821104	8.8±0.1	L3.5	L4	No binarity
2MASS J00531899-3631102		L3.5	L4	
SIMP 01365662+0933473	6.0±0.1		T2.5	
2MASS J01443536-0716142		L5		Red
2MASS J02182913-3133230		L3	L5.5	
DENIS-P J0255.0-4700	4.9±0.1	L8	L9	
2MASS J02572581-3105523	10.0±0.7	L8	L8.5	
2MASS J03480772-6022270			T7	
2MASS J03552337+1133437	9.1±0.1	L5	L3	Young
2MASSI J0423485-041403	13.9±2.1	L7.5	T0	Binary
2MASS J04390101-2353083	9.1±0.3	L6.5		
2MASS J04532647-1751543		L3pec		Young?
2MASS J05002100+0330501		L4	L4	
2MASS J05395200-0059019	12.2±4.5	L5	L5	No binarity
2MASS J06244595-4521548	11.9±0.6	L5pec	L5	
Gl 229B	5.8±0.4		T7pec	MP&Young
2MASS J10043929-3335189	17.0±1.6	L4	L5	
2MASS J11263991-5003550		L4.5	L6.5	Blue L
2MASS J13411160-3052505		L2pec	L2	
2MASS J18283572-4849046	11.9±1.1		T5.5	
2MASS J21513839-4853542			T4	

fit of the pseudocontinuum around the line. Then we divide the telluric by a black body synthetic spectra with the same temperature as the telluric star (Theodossiou & Danezis 1991). Finally, to calibrate in response, we use the package *noao.onedspec.telluric* from the sofware *Image Reduction and Analysis Facility*, (IRAF).

To make sure that the flux in the whole near-infrared spectra was correctly scaled, we calibrated flux of our near-infrared spectra using fluxes given by 2MASS (Two Micron All Sky Survey). We convolved our near-infrared spectra with J, H and K filter transmission curves of 2MASS. The resulting spectra were integrated. Then we calculate the flux in 2MASS for our targets in the J, H and K bands using 2MASS magnitudes (Cohen et al. 2003). Finally, we calculate the scaling factor for J, H and K bands and we multiply our near-infrared spectra in J, H and K filters to have the same flux as the given by 2MASS. We need to scale the flux from the optical spectra to be continue with the flux in the near-infrared spectra. In the overlapping wavelengths of the optical and near-infrared spectra, we calculate a scaling factor. This factor is calculated as the median of the flux in the overlapping wavelengths of the near-infrared spectra, divided by the median of the flux in the overlapping wavelengths of the optical spectra.

4. Empirical analysis

4.1 Finding L plus T brown dwarf binaries

Brown dwarf spectral binaries that are combinations of a L and a T brown dwarf have been in the past years widely studied (Burgasser et al. 2007, 2010). The combined spectra of these type of binaries are expected to show peculiar characteristics, as they are a combination of two quite different spectra, with different molecules absortions (Cushing et al. 2005a). In L brown dwarf spectra we find NaI, and two KI doublets in the J-band. In the H-band, appear the FeH absortion from 1.59 to 1.75 μm and in the K-band, we find the first overtone of band heads of ^{12}CO. In contrast, in T brown dwarf spectra we find also NaI and KI alkali lines like in the L-sequence, plus CH_4 bands in the range 1.15-1.25 μm. In the H-band there is CH_4 feature at 1.67 μm, and in the K-band we find CH_4 at 2.2 μm. Burgasser et al. (2010) describe differences of L plus T binaries in comparison with single template spectra: in general, they show bluer spectral energy distribution in the near-infrared, and in particular, some spectral features vary, like the CH_4 and H_2Oat 1.1 μm which are deeper for binaries and the CH_4 feature at 1.6 μm is stronger in comparison to the 2.2 μm band. Using the differences found, Burgasser et al. (2006) and Burgasser et al. (2010) define some spectral indices which help to detect L plus T brown dwarf binaries regarding these peculiar spectral characteristics. Objects that satisfy two criteria, are consider weak brown dwarf binary candidates, and objects that satisfy three or more criteria are strong binary candidates.

Calculating these indices was the first step of our empirical analysis, because just with eight plots we can select those objects from our sample that are candidates to be L plus T binaries. In Fig. .1 we show the result of calculating Burgasser et al. (2006) and Burgasser et al. (2010) indices. Regarding the result of these plot, object 2MASS J01365662+0933473 [hereafter SIMP0136] satisfy four criteria, objects 2MASSI J0423485-041403 [hereafter SD0423], which is a known binary, DENIS-P J0255.0-4700 [hereafter DE0255] and 2MASS J13411160-3052505 [hereafter 2M1341], satisfy two criteria. In Section 5., taking into account the whole analysis and the bibliography, we will further discuss whether, these objects are strong candidates to be binaries or not.

The next step in the empirical analysis consists on compare our spectra with several libraries of template spectra. We degrade our X-Shooter spectra to the resolution of each template before compare and we reinterpolated library spectra and X-Shooter spectra to the same grid. We used medium resolution template spectra of L and T field dwarfs (R$\sim$2000 McLean et al. 2003; Cushing et al. 2005b). We also compared our spectra to low resolution templates (R$\sim$120) of the SpeX Prism Spectral Library[1]. From this analysis we find the best matches to single and composite spectra, previously calibrated in flux to the same distance. To identify the best matches we use a χ^2 as explained in Cushing et al. (2008) and visual inspection. We show the best match to potential L plus T objects in Appendix 7..

[1]http://pono.ucsd.edu/$\sim$adam/browndwarfs/spexprism/

After compare to single and composite spectra, we find best matches to these selected objects. Plots to the following results are available in Appendix 7.. The best match to object SD0423 is a composite spectra formed by 2MASS15150083+4847416 (L6) and SDSS125453.90-012247.4 (T2). The best match to SIMP0136 spectra is the spectrum of SDSS152103.24+013142.7, which is a single T2 template. Object DE0255 is well reproduced by several single SpeX late L and early T template spectra: SDSS085234.90+472035.0 (L9.5), SDSS105213.51+442255.7 (T0.5) and 2MASS 0328426+230205 (L9.5), among others. Nevertheless, there are also good agreements of these spectra to composite spectra: SDSS 103931.35+325625.5 (T1) and SDSS 163030.53+434404.0 (L7) and SDSS 035104.37 (T1) and SDSS 104409.43+042937.6 (L7). Object 2M1341 is classified as L2 with peculiar spectra. The best matches to this object are actually combinations of L plus T brown dwarfs templates: SDSS 175805.46+463311.9 (T6.5) and GJ1048B (L1) and 2MASS 1217110-031113 (T7) and GJ1048B (L1). Nonetheless, none of the matches are able to fully reproduce features in the H and K bands.

4.2 Finding L plus L or T plus T brown dwarf binaries

Spectroscopy search of brown dwarf binary pairs L plus L and T plus T has not been as developed as for L plus T binaries. Differences between L or T brown dwarfs of different spectral types is mainly in the spectral energy distribution, but the difference in spectral features is almost neglible, therefore the search of pairs of binaries with similar spectral types becomes challenging.

Before comparing to the set of libraries used in Section 4.1, we first test the effectiviy of our method using synthetic binaries. For this we choose several L and T single and not peculiar brown dwarfs from the SpeX library. Then we calibrate their fluxes to the same distance, using the absolute magnitude-spectral type relation published by Dupuy & Liu (2012). We combine different pairs of L brown dwarfs with L brown dwarfs and different pairs of T brown dwarfs with T brown dwarfs, creating L plus L and T plus T synthetic binaries. We produce several L plus L brown dwarf binary pairs: 2MASS01303563-4445411B (L6) [hereafter 2M1303-4445] and DENIS-P J220002.05-303832.9B (L0) [hereafter DE2200-3038], SDSS J111320.16+343057.9 (L3) [hereafter SD1113+3430] and DE2200-3038 (L0), and SDSS J121951.45+312849.4 (L8) [hereafter SD1219+3128] and SDSS J111320.16+343057.9 (L3) [hereafter SD1113+3430]. We create two T plus T brown dwarf binary pairs: 2MASSI J1553022+153236 (T7) [hereafter 2M1553+1532] and 2MASS J11220826-3512363 (T2) [hereafter 2M11220-3512], and SDSS J015141.69+124429.6 (T1) [hereafter SD0151+1244] 2MASS J04070885+151456 (T5) [hereafter 2M0407+1514] and a L plus T pair: SDSS J104409.43+042937.6 (L7) [hereafter SD1044+0429] and 2M11220-3512 (T2).

We compare L plus L, T plus T and L plus T brown dwarf binaries pairs mention before to single SpeX templates and find best matches. Our objective is to test if synthetic L plus L and T plus T binaries can be found by comparing to spectral library spectra. Figures showing best matches are shown in Appendix 7.. For L plus L pairs, 2M1303-4445 (L6) and DE2200-3038 (L0), SD1113+3430 (L3) and DE2200-3038 (L0), and SD1219+3128 (L8) and SD1113+3430 (L3), best matches are: 2MASS 0345432+254023 (L1) and 2MASS 2130446-084520 (L1.5) for L0+L6, 2MASS 2130446-084520 (L1.5) and HD 89744B (L early) for L3+L0 and DENIS-P J1228-1547 (L6±2) and 2MASS J14283132+5923354 (L4) for L3+L8, Spex single templates. In Appendix 7. we show two best matches for ev-

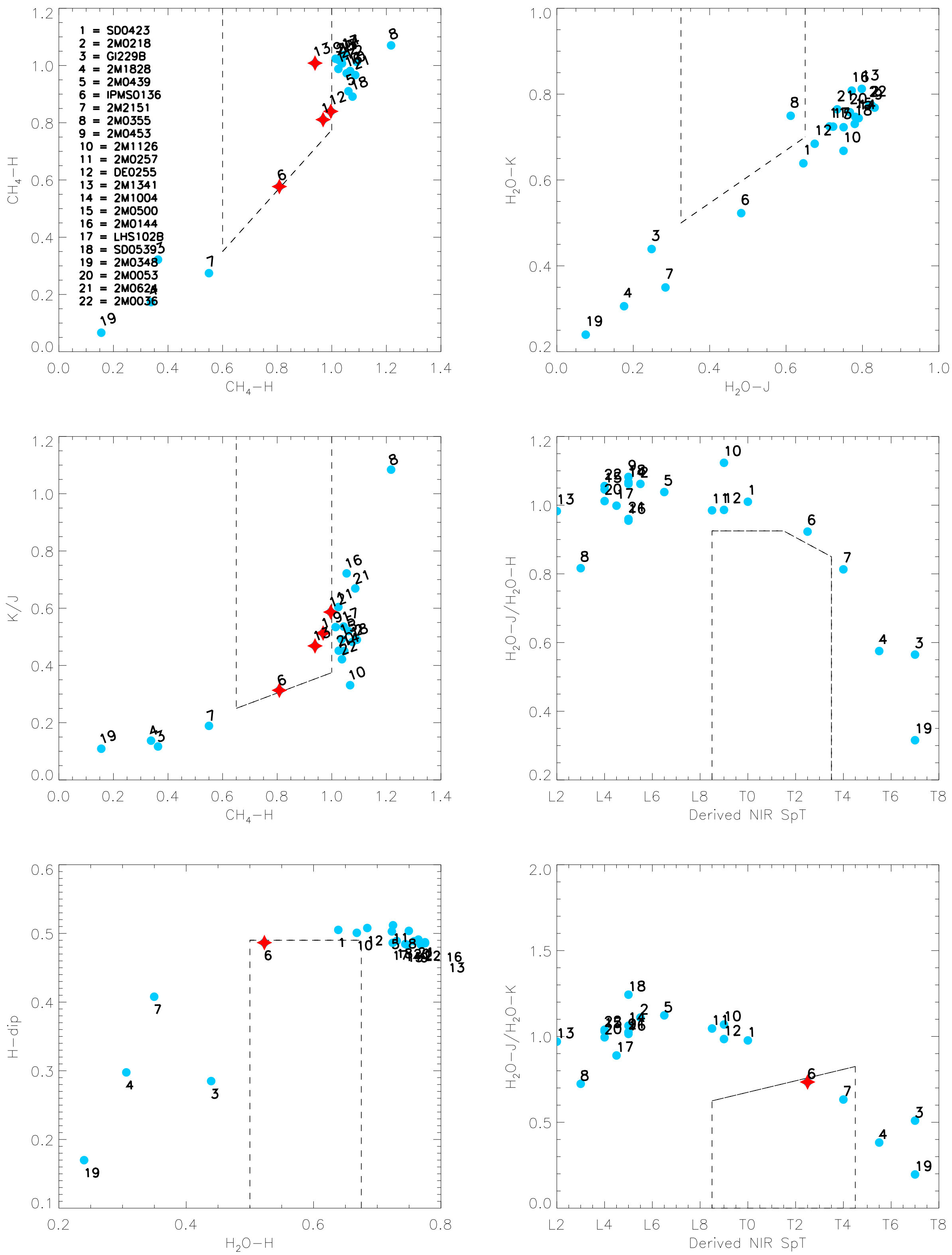

Figure .1: Spectral index selection. We compare H_2O-J vs H_2O-K, CH_4-H vs CH_4-K, CH_4-H vs K/J, H_2O-H vs H-dip, and finally the estimated spectral type using SpeX template spectra vs H_2O-J/H_2O-H and H_2O-J/CH_4-K. Numbers 1-22 correspond to the name of our objects.

ery synthetic binary. For T plus T synthetic binary pairs, 2M1553+1532 (T7) and 2M11220-3512 (T2), and SD0151+1244 (T1) and 2M0407+1514 (T5), the best matches are: SDSS J120602+281328 (T3) and SDSS 175032+175903 (T3.5) for T2+T7, SDSS J102109-030420 (T3) and SDSS143945+304220 (T2.5) for T1+T5. Spex single templates. The best match found for the synthetic spectra composed by SD1044+0429 (L7) and 2M11220-3512 (T2) is 2MASS J22541892+3123498 [hereafter 2M2254+3123]. 2M2254+3123 is a strong brown dwarf binary candidate (Burgasser et al. 2010) with T4 spectral type.

From this analysis, we conclude that L plus L and T plus T brown dwarfs binaries may not be straightforward to detect just by comparing with single or composite spectral libraries. Therefore, additional data will be necessary to find these binaries, i.e. parallaxes or high resolution imaging. From our 22 objects sample, there are distances for 12 of the objects, with precisions around 10%. Color-magnitude diagrams (CMD) showing J-H and J-K in the MKO (Mauna Kea Observatory) system versus absolute magnitude in J are presented for these objects (Fig. .2). In Fig. .2, the two known binaries from our sample sand out over objects with their same spectral types, together with Gl229B. Nevertheless, photometry of Gl229B it may not be relible enough, because of the proximity of the companion. For the rest of the objects in the same, it is difficult to extract conclusions, as there are not clear outliers.

In Table .2 we show all best matches of our objects to spectral libraries McLean et al. (2003), Cushing et al. (2005b) and Spex libraries. We show the best matches plots in Section 7.. In Table .2 we do not include those objects for which we did not find a match to spectra from spectral libraries. For objects 2M0348 (T7), Gl229B (T7), 2M1828 (T5.5) and 2M2151 (T4) we did not find lots of late T template spectra in McLean et al. (2003) and Cushing et al. (2005b) libraries and in SpeX, which can explain the lack of decent matches to these objects. Objects 2M0624 (L5:) and 2M1126 (L6.5:) have peculiar spectra, so we can expect not to find a acceptable match. Object 2M0355 (L5) is a young object (Allers & Liu 2013), therefore we can expect not to find a decent match to spectra from field brown dwarfs in McLean et al. (2003), Cushing et al. (2005b) and SpeX.

5. Revised properties

In this section we aim to revise properties of some of our objects taking into account our results from Section 4..

5.1 SIMP 01365662+0933473

Object SIMP 0136 was discovered by Artigau et al. (2006) in the SIMP (Sondage Infrarouge de Movement Propre) near infrared proper motion survey, and it was classified as a T2.5. Goldman et al. (2008) searched for companions using high resolution imaging with NACO at VLT with sensitivity of 0.2” (1-40 AU), but no companions were found. Artigau et al. (2009) detected photometric variability in J and K band with a modulation of ∼2.4 h and an amplitude of 50 mmag. Radigan et al. (2012) calculated the amplitude of the variability for a object similar to SIMP 0136 (2MASS J21392676+0220226, T1.5) if it were produced by a companion, but the variability in that case would be much smaller than the variability found. Apai et al. (2013) explain this variability with a mixture of thick and thin patchy iron and silicate clouds covering the surface of the object.

Table .2: Best matches spectra coming from spectral libraries

Name	Best match	Library
LHS 102B	SDSS 083506.16+195304.4 (L4.5)	SpeX
2MASS J00361617+1821104	2MASS 02081833+2542533 (L1)	Cushing et al. (2005b)
2MASS J00531899-3631102	2MASS 15074769-1627386 (L5)	Cushing et al. (2005b)
2MASS J01443536-0716142	2MASS 22244381-0158521 (L4.5)	Cushing et al. (2005b)
2MASS J02182913-3133230	Kelu-1 (L2)	Cushing et al. (2005b)
2MASS J04390101-2353083	2MASS 15150083+4847416 (L6)	Cushing et al. (2005b)
2MASS J04532647-1751543	2MASS 15150083+4847416 (L6)	Cushing et al. (2005b)
2MASS J05002100+0330501	2MASS 15065441+1321060 (L3)	Cushing et al. (2005b)
2MASS J05395200-0059019	2MASS 18131803+5101246 (L5)	SpeX
2MASS J10043929-3335189	2MASS 11463449+2230527AB (L3)	Cushing et al. (2005b)

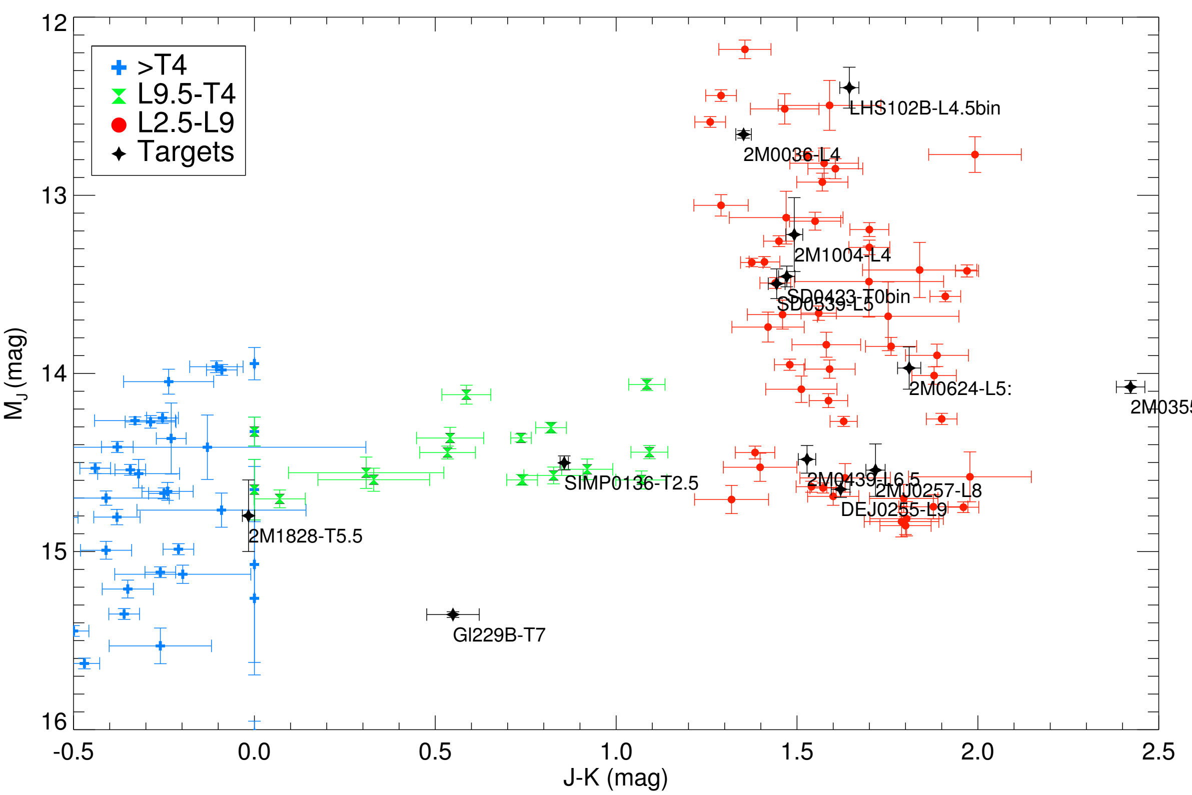

Figure .2: Color magnitude diagram showing brown dwarfs with measured parallax from Dupuy & Liu (2012) together with our targets.

In Section 4.1 we utilized indices by Burgasser et al. (2006) and Burgasser et al. (2010) to select potential L plus T brown dwarf binary candidates. Object SIMP 0136 was selected as a strong brown dwarf binary candidate, as it appears in the selected area of four of the plots in Figure .1. These indices are made to select peculiar spectral characteristics that appear usually in binary L plus T brown dwarf spectra. Nevertheless, if variability is produced by a mixture of thick and thin clouds in the brown dwarf atmosphere, similar peculiar spectral characteristics would appear in brown dwarf spectra. We also compare our X-Shooter spectra with several single and composite of brown dwarf spectra of several spectral libraries (McLean et al. (2003), Cushing et al. (2005b) and Spex) and we found a best match with SDSS152103.24+013142.7 (T2) (see Fig. 5.1), which contradicts also possibility of being binary.

Parallax for SIMP 0136 is know, but not published (Smart, private comm.). Utilizing parallax we place the object in a CMD diagram together with objects published in Dupuy & Liu (2012) (see Fig. .2) and we compare this object with objects of similar spectral type. We do not find overluminosity indicating similar spectral types binaries (see Fig. .2).

5.2 DENIS-P J0255.0-4700

Object DE0255 was discovered by Martín et al. (1999) and it was classified as a peculiar L6. Koen et al. (2005) reported evidence of variability in the optical with a frequency of 6.7 d^{-1}. Costa et al. (2006) reported absolute parallax for this object: $\pi = 201.37 \pm 3.89$ mas. Burgasser et al. (2008) classified this object in the optical as a L8 and in the near infrared as a L9. Finally, Reid et al. (2008) searched for multiplicity for this object using NICMOS NIC1 camera on the Hubble Space Telescope and obtain high-resolution, but the result was negative.

In Section 4.1 was selected as a weak candidate to be brown dwarf L plus T binary by Burgasser et al. (2006) and Burgasser et al. (2010) indices. We compared DE0255 near infrared X-Shooter spectra to single and composite spectra from McLean et al. (2003), Cushing et al. (2005b) and Spex libraries. We found decent matches to both single late L early T spectra and to composite spectra of late L plus early T spectra.

Costa et al. (2006) published parallax for this object, we plot this object in a CMD diagram together with objects published in Dupuy & Liu (2012) (see Fig. .2), as done for SIMP0136 previously, and no overluminosity is found. Therefore, either DE0255 is not a binary or it is a very unequal binary system.

5.3 2MASS J13411160-3052505

Object 2M1341 is the less studied object from our sample. It was discovered by Reid et al. (2008) using 2MASS data. Kirkpatrick et al. (2011) classified as a L2 with a peculiar spectrum. Finally, Koen (2013) found also variability of 67 mmag in I-band in a period of two days.

In Section 4.1 was selected as a weak candidate to be brown dwarf L plus T binary by Burgasser et al. (2006) and Burgasser et al. (2010) indices. We compared 2M1341 X-Shooter near infrared spectrum to McLean et al. (2003), Cushing et al. (2005b) and Spex libraries. Best matches to this object were composite spectra of L plus T brown dwarf spectra. The best match were SDSS 175805.46+463311.9 (T6.5) and GJ1048B (L1) and 2MASS 1217110-031113 (T7) and GJ1048B (L1). Nonetheless, none of the matches are able to fully reproduce features in the H and K bands. Parallax for this object has not been yet published. Therefore, we can not confirm or refute if this object is a binary.

5.4 Gl229B

Object Gl229B was discovered by Nakajima et al. (1995), and it was the first T brown dwarf discovered. It is companion of Gl229A. Jenkins et al. (2009) provided spectral types for Gl229A (M1V). Faherty et al. (2009) classified Gl229B as a T7 brown dwarf with peculiar spectra. Parallax for this object was published by van Leeuwen (2007) using Hipparcos data (π = 173.81±0.99 mas). Burgasser et al. (2006) confirmed that the system Gl229A and Gl229B is metal-poor, as Leggett et al. (2002) found before.

We did not find a best match to this object to other object in McLean et al. (2003), Cushing et al. (2005b) and Spex libraries. There is no photometry in H band for this object in 2MASS, due to the proximity of Gl229A. Therefore, we can only plot in the J-K vs M_J CMD (see Fig. .2). In Fig. .2 Gl229B is found together with much brighter objects. This could be an indicative of binarity. Nonetheless we cannot rely on this result as the photometry for Gl229B is contaminated by the photometry of Gl229A.

6. Conclusions

Peculiar brown dwarf spectra or the divergence in optical and near-infrared spectral type classification may indicate tight brown dwarfs binary systems. A proper characterization of these peculiar spectra may help either to understand the formation mechanisms of brown dwarfs and to calculate the binarity fraction for brown dwarfs with better precision.

We observed and analyzed 22 optical and near infrared medium resolution spectra of brown dwarfs with spectral types between L2 and T7. Our sample of objects had peculiar spectral characteristics or different classifications in the optical and in the near infrared. Two objects from our sample are known binaries, that allow us to test our analysis. We performed observations using VLT/X-Shooter between October 2009 and June 2010. Spectral resolution of our spectra is R∼5400 in the optical and R∼3300 in the near infrared.

Among the whole sample, we aim to find first potential L plus T brown dwarf binaries, because their peculiar spectral characteristics have been broadly studied. Burgasser et al. (2006, 2010) developed a set of spectral indices that allow to identify potential L plus T binary candidates. We used his method to identify this objects in our sample. We selected four objects as potential L plus T binary candidates: SIMP0136 (T2.5), SD0423 (T0, known binary), DE0255 (L9) and 2M1341 (L2, peculiar spectra). Afterward, we compared these four selected objects with spectral libraries of field brown dwarfs (McLean et al. (2003), Cushing et al. (2005b) and Spex) and composite spectra of these libraries. We select the best match for every of this objects with exception of SD0423. Best match for SIMP0136 is object 2MASS J21392676+0220226 (T1.5) and parallax do not reveal overluminosity. Nevertheless, DE0255, is well reproduced for several single late L and early T brown dwarfs and composite of them, but parallax do nor reveal any overluminosity. Finally, the spectrum of object 2M1341 is just reproduced by a combination of the spectra from SDSS 175805.46+463311.9 (T6.5) and GJ1048B (L1) and the combination of the spectrum of 2MASS 1217110-031113 (T7) and GJ1048B (L1).

We studied if it is possible to find also L plus L or T plus T brown dwarfs binaries using the method of comparing to several spectral libraries. We created several synthetic binaries of L plus L spectra and several synthetic binaries of T plus T spectra, previously calibrated to the same distance. We compared all synthetic binaries to McLean et al. (2003), Cushing et al. (2005b) and Spex libraries and look for the best matches to single and composite spectra. Best matches for all the synthetic binaries created were single spectra, with an intermediate spectral type between the primary and the secondary from the binary. We result can be expected, because the main difference between a L0 and a L8 brown dwarf is the SED, as well as for T1 and T7. As there are not different spectral characteristics beside the difference in SED, peculiarities in L plus L and T plus T brown dwarf spectra are difficult to find. In these cases, we need supplementary parallax measurements or high resolution imaging to confirm or discard binarity. We also compared the rest of the objects in our sample to citetMcLean, Cushing et al. (2005b) and Spex libraries. In these case, when we find a match is usually with a single spectra from one of these libraries.

Optical and near infrared spectra reported in this paper will serve as templates for future studies in any of these wavelengths. In the near future, Gaia satellite will release high precision parallaxes of more than one billion of objects in the Milky Way, including hundred of brown dwarfs. These parallaxes will allow us to detect the overluminosity of brown dwarf binaries.

Acknowledgments. We gratefully acknowledge ESO allocation time committee and Paranal Observatory staff for allowing the performance of these observations. We thank Adam Burgasser for providing and maintain The SpeX Prism Spectral Libraries: http://pono.ucsd.edu/ adam/browndwarfs/spexprism/. We thank Adam Burgasser, Daniella Bardalez Gagliuffi, Jackie Radigan and Esther Buenzli for their help in the development of this paper.

7. Appendix

7.1 Synthetic L plus L or T plus T best matches to template spectra

References

Allard, F., Hauschildt, P. H., Alexander, D. R., Tamanai, A., & Schweitzer, A. 2001, ApJ, 556, 357

Allen, P. R., Koerner, D. W., McElwain, M. W., Cruz, K. L., & Reid, I. N. 2007, AJ, 133, 971

Allers, K. N. & Liu, M. C. 2013, ArXiv e-prints

Apai, D., Radigan, J., Buenzli, E., et al. 2013, ApJ, 768, 121

Artigau, É., Bouchard, S., Doyon, R., & Lafrenière, D. 2009, ApJ, 701, 1534

Artigau, É., Doyon, R., Lafrenière, D., et al. 2006, ApJ, 651, L57

Basri, G. & Martín, E. L. 1999, AJ, 118, 2460

Blake, C. H., Charbonneau, D., & White, R. J. 2010, ApJ, 723, 684

Bouy, H., Brandner, W., Martín, E. L., et al. 2003, AJ, 126, 1526

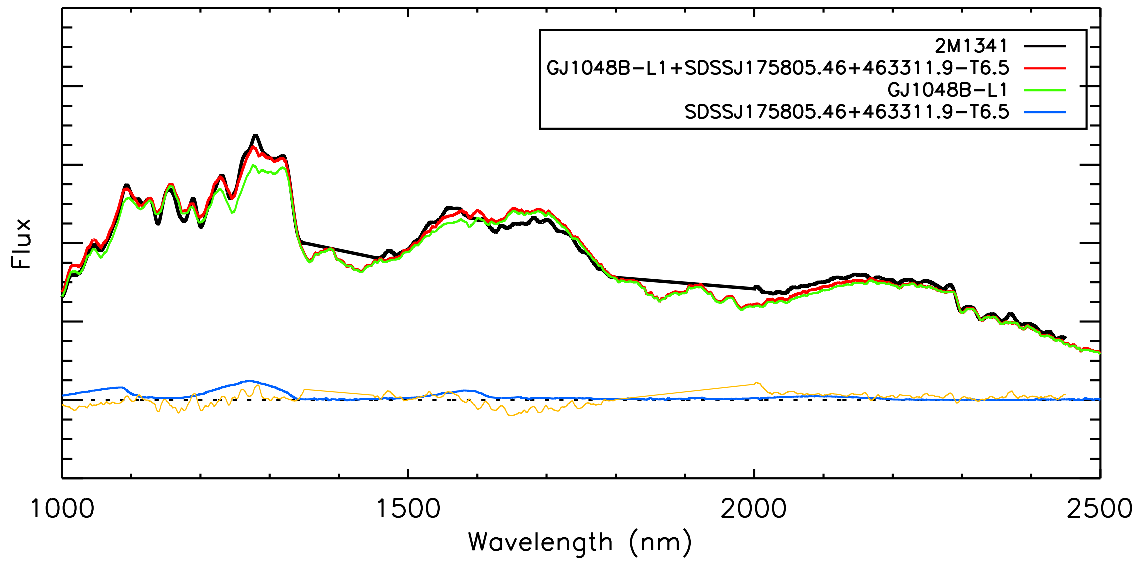

Figure .3: Best matches for object 2M1341 (L2, peculiar). Object SDSS175805.46+463311.9 has T6.5 spectral type, GJ1048B is a L1 and 2MASS1217110-031113 is a T7. In black we show the synthetic T2+T7 spectrum, in blue the single best match object and in green residuals.

Bouy, H., Duchêne, G., Köhler, R., et al. 2004, A&A, 423, 341

Burgasser, A. J., Cruz, K. L., Cushing, M., et al. 2010, ApJ, 710, 1142

Burgasser, A. J., Cruz, K. L., & Kirkpatrick, J. D. 2007, ApJ, 657, 494

Burgasser, A. J., Geballe, T. R., Leggett, S. K., Kirkpatrick, J. D., & Golimowski, D. A. 2006, ApJ, 637, 1067

Burgasser, A. J., Kirkpatrick, J. D., Reid, I. N., et al. 2003, ApJ, 586, 512

Burgasser, A. J., Looper, D. L., Kirkpatrick, J. D., Cruz, K. L., & Swift, B. J. 2008, ApJ, 674, 451

Burrows, A. & Sharp, C. M. 1999, ApJ, 512, 843

Close, L. M., Siegler, N., Freed, M., & Biller, B. 2003, ApJ, 587, 407

Cohen, M., Wheaton, W. A., & Megeath, S. T. 2003, AJ, 126, 1090

Costa, E., Méndez, R. A., Jao, W.-C., et al. 2006, AJ, 132, 1234

Cushing, M. C., Marley, M. S., Saumon, D., et al. 2008, ApJ, 678, 1372

Cushing, M. C., Rayner, J. T., & Vacca, W. D. 2005a, ApJ, 623, 1115

Cushing, M. C., Rayner, J. T., & Vacca, W. D. 2005b, ApJ, 623, 1115

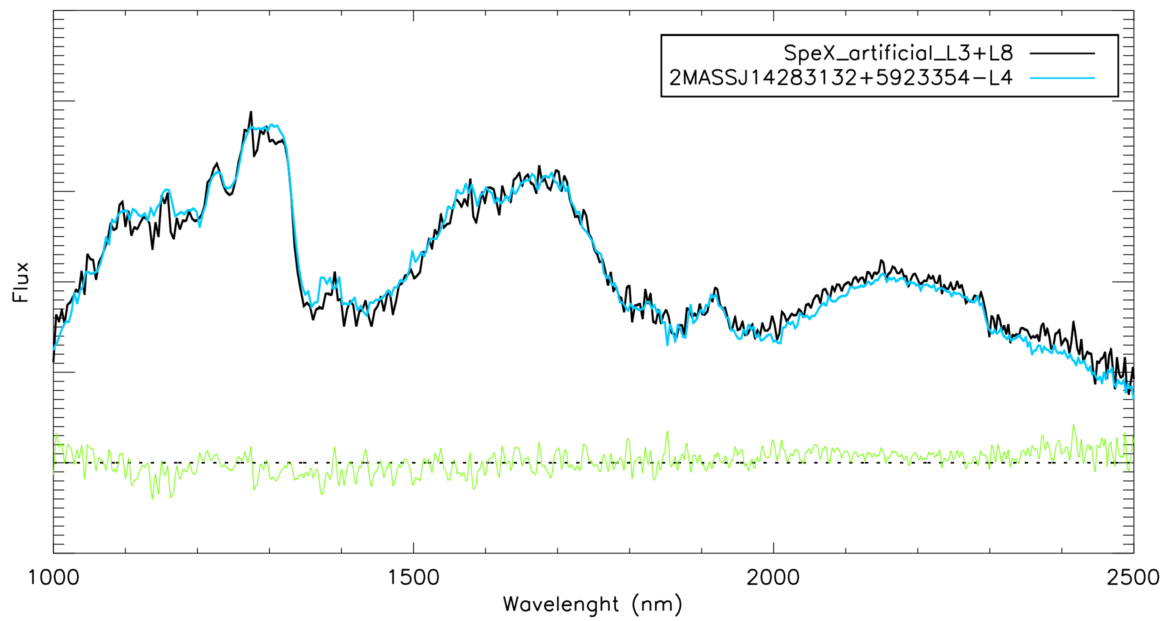

Figure .4: Best matches for a L3 (SDSSJ111320.16+343057.9) + L8 (SDSSJ121951.45+312849.4) synthetic binary.

Dupuy, T. J. & Liu, M. C. 2012, ApJS, 201, 19

Dupuy, T. J., Liu, M. C., Bowler, B. P., et al. 2010, ApJ, 721, 1725

Dupuy, T. J., Liu, M. C., & Ireland, M. J. 2009, ApJ, 699, 168

Faherty, J. K., Burgasser, A. J., Cruz, K. L., et al. 2009, AJ, 137, 1

Gizis, J. E., Reid, I. N., Knapp, G. R., et al. 2003, AJ, 125, 3302

Goldman, B., Bouy, H., Zapatero Osorio, M. R., et al. 2008, A&A, 490, 763

Jenkins, J. S., Ramsey, L. W., Jones, H. R. A., et al. 2009, ApJ, 704, 975

Joergens, V. 2008, A&A, 492, 545

Kirkpatrick, J. D., Cushing, M. C., Gelino, C. R., et al. 2011, ApJS, 197, 19

Koen, C. 2013, MNRAS, 428, 2824

Koen, C., Tanabé, T., Tamura, M., & Kusakabe, N. 2005, MNRAS, 362, 727

Koerner, D. W., Kirkpatrick, J. D., McElwain, M. W., & Bonaventura, N. R. 1999, ApJ, 526, L25

Konopacky, Q. M., Ghez, A. M., Barman, T. S., et al. 2010, ApJ, 711, 1087

Kraus, A. L. & Hillenbrand, L. A. 2012, ApJ, 757, 141

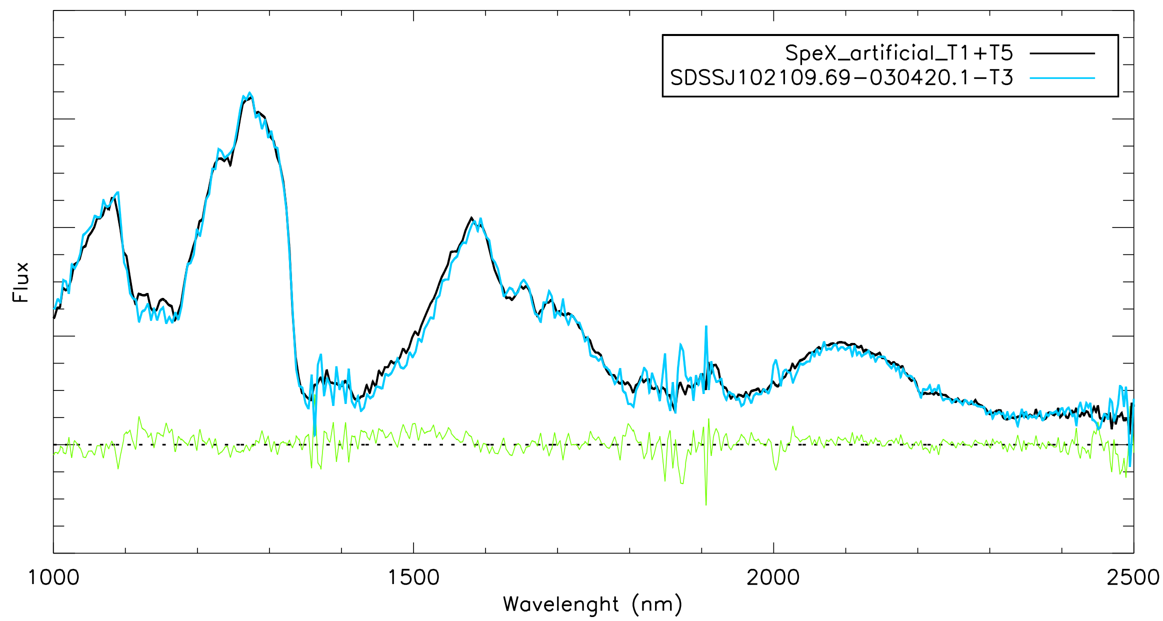

Figure .5: Best matches for a T1 (SDSSJ015141.69+124429.6) + T5 (2MASSJ04070885+1514565) synthetic binary.

Leggett, S. K., Hauschildt, P. H., Allard, F., Geballe, T. R., & Baron, E. 2002, MNRAS, 332, 78

Liu, M. C., Dupuy, T. J., & Ireland, M. J. 2008, ApJ, 689, 436

Lodders, K. 1999, ApJ, 519, 793

Luhman, K. L., Allers, K. N., Jaffe, D. T., et al. 2007, ApJ, 659, 1629

Lunine, J. I., Hubbard, W. B., & Marley, M. S. 1986, ApJ, 310, 238

Marley, M. 2000, in Astronomical Society of the Pacific Conference Series, Vol. 212, From Giant Planets to Cool Stars, ed. C. A. Griffith & M. S. Marley, 152

Marley, M. S. & Ackerman, A. S. 2001, ArXiv Astrophysics e-prints

Martín, E. L., Basri, G., Brandner, W., et al. 1998, ApJ, 509, L113

Martín, E. L., Delfosse, X., Basri, G., et al. 1999, AJ, 118, 2466

McLean, I. S., McGovern, M. R., Burgasser, A. J., et al. 2003, ApJ, 596, 561

Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., et al. 1995, *Nature* , 378, 463

Radigan, J., Jayawardhana, R., Lafrenière, D., et al. 2012, ApJ, 750, 105

Reid, I. N., Cruz, K. L., Burgasser, A. J., & Liu, M. C. 2008, AJ, 135, 580

Reid, I. N., Gizis, J. E., Kirkpatrick, J. D., & Koerner, D. W. 2001, AJ, 121, 489

Theodossiou, E. & Danezis, E. 1991, Ap&SS, 183, 91

Tsuji, T., Ohnaka, K., Aoki, W., & Nakajima, T. 1996, A&A, 308, L29

van Leeuwen, F. 2007, A&A, 474, 653