

The Gaia Ultra-Cool Dwarf Sample – III: seven new multiple systems containing at least one *Gaia* DR2 ultracool dwarf.

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ABSTRACT

We present 10 new ultracool dwarfs in seven wide binary systems discovered using *Gaia* second data release data, identified as part of our Gaia Ultra-Cool Dwarf Sample project. The seven systems presented here include an L1 companion to the G5 IV star HD 164507, an L1: companion to the V478 Lyr AB system, an L2 companion to the metal-poor K5 V star CD-28 8692, an M9 V companion to the young variable K0 V star LT UMa, and three low-mass binaries consisting of late Ms and early Ls. The HD 164507, CD-28 8692, V478 Lyr, and LT UMa systems are particularly important benchmarks, because the primaries are well characterized and offer excellent constraints on the atmospheric parameters and ages of the companions. We find that the M8 V star 2MASS J23253550+4608163 is ~ 2.5 mag overluminous compared to M dwarfs of similar spectral type, but at the same time it does not exhibit obvious peculiarities in its near-infrared spectrum. Its overluminosity cannot be explained by unresolved binarity alone. Finally, we present an L1+L2 system with a projected physical separation of 959 au, making this the widest L + L binary currently known.

Key words: binaries: visual – brown dwarfs – stars: individual: HD 164507, V478 Lyr, CD-28 8692, LT UMa – stars: low-mass.

1 INTRODUCTION

Ultracool dwarfs (UCDs, spectral type $\geq M7$) in binary systems with main-sequence and post-main-sequence stars are valuable benchmarks (Pinfield et al. 2006), providing robust tests of ultracool atmospheric and evolutionary models. Under the reasonable assumption of common origin, a bright main-sequence primary provides constraints on the metallicity and the age of a system, two parameters that are currently difficult to infer for isolated UCDs.

UCDs are a mixture of the lowest mass hydrogen fusing stars and substellar non-hydrogen-fusing objects. Mass, age, metallicity,

and luminosity are degenerate parameters for these objects, and the presence (and evolution) of dust clouds in the photosphere further complicates the interpretation of their spectra (Burrows, Sudarsky & Hubeny 2006; Saumon & Marley 2008). Furthermore substellar UCDs overlap in both mass and temperature with the gaseous giant planets in exosolar systems (e.g. Faherty et al. 2016), but can be studied without the additional complication of the planets' vicinity to a bright host star. A full understanding of ultracool atmospheres is therefore of vital importance if we wish to understand exoplanets and their formation and evolution.

The recent second data release (DR2) from the ESA mission *Gaia* (Gaia Collaboration et al. 2016a, 2018) provides exquisite astrometry for ~ 1.3 billion objects within our Galaxy (Lindegren et al. 2018), allowing access to a huge population of wide binaries consisting of an UCD in a system with a star or white dwarf

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(Marocco et al. 2017). In particular, the greatly increased volume probed by *Gaia*, and the resulting increased pool of potential primary stars, offers for the first time the possibility to map the full age–temperature–metallicity parameter space, large regions of which are currently undersampled or completely unexplored (see e.g. Day-Jones et al. 2011; Deacon et al. 2014; Marocco et al. 2017). While the advent of *Gaia* expands the pool of potential primaries, existing optical and near-infrared (IR) surveys, and the astrometric catalogues that spawned from them (e.g. the United Kingdom Infrared Deep Sky Survey Large Area Survey, Smith et al. 2014; the Variables in the Via Lactea Infrared Astrometric Catalogue, Smith et al. 2018; CatWISE, Eisenhardt et al. 2020), grant access to a vast population of UCDs across spectral types M, L, T, and Y. We have therefore set out to complete the nearby census of these objects, to fully explore and characterize ultracool atmospheres.

In this paper, we present seven new multiple systems containing at least one *Gaia* DR2 UCD component.

In Section 2, we describe our candidate selection; in Section 3, we summarize observing and data reduction procedures; in Section 4, we discuss in more detail the newly discovered systems; in Section 5, we compare the main features in the spectra of the new UCDs; and finally in Section 6, we summarize our findings and discuss future work.

2 CANDIDATE SELECTION

We identified an initial list of 8013 UCD candidates from the *Gaia* DR2 catalogue as follows. First, we queried the catalogue for *Gaia* sources fainter than the maximum brightness that an UCD at the measured parallax could have, as predicted by the BT-Settl models (Allard et al. 2012a; Allard, Homeier & Freytag 2013). The maximum distance is 373 pc, the distance at which the brightest, hottest UCD ($T_{\text{eff}} \sim 2500$ K) would be fainter than the *Gaia* limiting magnitude ($G = 20.7$ mag). We required the $G - G_{RP}$ colour to be redder than 1.4 mag (since UCDs are typically redder than that; Smart et al. 2017, 2019). To minimize the number of sources with spurious astrometric measurements, we removed candidates within 5° of the Galactic plane and inside an ellipse centred at the Galactic centre with semimajor axis along the Galactic longitude axis of 50° , and 8° along the Galactic latitude axis. To retain only reliable astrometric measurements, we required sources to have more than six visibility periods and astrometric excess noise lower than 5 mas. We computed posterior probability densities of the distance given the parallax measurements and associated uncertainties using an exponentially decreasing constant volume density prior, and selected sources with a posterior probability to be within 373 pc greater than 0.5. We then fit a principal curve (Hastie & Stuetzle 1989) in the M_G versus $G - G_{RP}$ plane to the values of the resulting set, and calibrated the curve in effective temperature using the spectral types of sources in the *Gaia* Ultra-Cool Dwarfs Sample (GUCDS, Smart et al. 2017, 2019) and the Stephens et al. (2009) conversion between spectral types and effective temperatures. Finally, we computed the projections of the UCD candidate positions in the M_G versus G_{RP} plane along the principal curve and assigned effective temperatures accordingly. A cut at $T_{\text{eff}} \leq 2500$ K resulted in the 8013 candidates mentioned above.

We searched for binaries among these 8013 UCD candidates using the criteria defined in Smart et al. (2019, hereafter GUCDS II):

$$\begin{aligned} \rho &< 100 \varpi \\ \Delta\varpi &< \max[3\sigma_\varpi, 1 \text{ mas}] \end{aligned}$$

$$\begin{aligned} \Delta\mu &< 0.1 \mu \\ \Delta\theta &< 15^\circ, \end{aligned} \quad (1)$$

where ρ is the separation on the sky in arcseconds, $\Delta\varpi$ is the difference between the candidate UCD and primary parallax, ϖ and σ_ϖ are the parallax and parallax uncertainty for the UCD (in mas), $\Delta\mu$ is the difference of the total proper motions, and $\Delta\theta$ is the difference of the position angles. The maximum ρ was chosen to correspond to 100 000 au as a conservative upper limit for the projected physical separation (s). This separation meets the binding energy criterion of $|U_g^*| > 10^{33}$ J as developed by Caballero (2009) for a system of a 0.1 and a 2 M_\odot objects. The parallax criterion is a compromise between a standard 3σ criterion, and a more conservative 1.0 mas difference to allow for parallaxes that had unrealistically low errors. For the proper motion, using a standard 3σ criterion would remove nearby objects with significant orbital motion, so we choose a conservative 10 per cent agreement, which is large enough to accommodate most orbital motions but small enough to reduce false positives. As discussed in GUCDS II, these criteria fail for the nearby binary systems GJ 1048 A/B and G 239-25 A/B (in both cases because the modulus of the proper motions differs by more than 10 per cent). Therefore, our catalogue of binary candidates should not be regarded as complete.

Of the 8013 UCD candidates, 840 have a possible companion according to the criteria above. The seven systems presented here are those that we could observe during our observing nights at the Palomar Observatory. We present their astrometric properties and spectral types in Tables 1 and 2. We collected optical and near-IR photometry for both components of our newly discovered systems from *Gaia* DR2, the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), the Panoramic Survey Telescope and Rapid Response System Data Release 1 (PanSTARRS DR1; Chambers et al. 2016), and AllWISE (Cutri et al. 2013). The photometry is also presented in Tables 1 and 2. In Fig. 1, we show a colour–magnitude diagram based on *Gaia* colours and astrometry. The small grey points are objects in *Gaia* DR2 nominally within 50 pc, selected using equations (C.1) and (C.2) from Lindegren et al. (2018). Red points are UCDs identified in *Gaia* DR2 by GUCDS II. The position of the seven systems presented here is highlighted with different symbols, with the primary plotted in blue and the companion in red. Two objects stand out at first glance: HD 164507 B, and 2MASS J23253550+4608163. We will discuss their properties in Sections 4.1 and 4.4.

3 OBSERVATIONS

We obtained near-IR spectra for the UCDs in our newly discovered binary systems using TripleSpec on the 200-inch Hale Telescope at the Palomar Observatory on 2018 April 27–29 and October 16 and 18, and 2019 April 16 (proposals: 2018A J12, 2018B J08, and 2019A J14; PI: Mamajek; see Appendix A). TripleSpec is a near-IR echelle spectrograph, that delivers a resolution of 2500–2700 over the wavelength range 1.0–2.4 μm (Herter et al. 2008).

Targets were observed following a standard ABBA nodding pattern with a nod throw of 11 arcsec. The slit was aligned to the parallactic angle to minimize atmospheric distortion, with the exceptions of HD 164507 B, V478 Lyr C, and 2MASS J232535.09+460809.3, for which we rotated the slit to avoid the bright primary. We observed an A0 V star (selected using the Gemini Telluric Standard Search

Table 1. Astrometry, photometry, and spectral types for the HD 164507 AB, V478 Lyr ABC, CD-28 8692 AB, and 2MASS J1839+4424 AB systems.

	HD 164507		V478 Lyr		CD-28 8692		2MASS J1839+4424	
	A	B	AB	C	A	B	A	B
RA (hh:mm:ss)	18:00:57.22	18:00:58.48	19:07:32.52	19:07:33.23	11:10:25.97	11:10:29.21	18:39:29.22	18:39:27.40
Dec. (dd:mm:ss.s)	+ 15:05:35.3	+ 15:05:18.3	+ 30:15:17.8	+ 30:15:32.1	-29:24:51.5	-29:25:19.8	+ 44:24:41.2	+ 44:24:51.0
Sep. (arcsec)	25.01		17.05		50.91		21.89	
Sep. (au)	1136		462		2026		811	
PA (deg)	132.58		32.63		123.84		296.62	
Sp. type	G5 IV ¹	L1	G8 V SB ²	L1:	K5 V ³	L2	M9 V ⁴	L2
ϖ (mas)	22.009 ± 0.037	24.8 ± 1.4	36.877 ± 0.026	37.02 ± 0.46	25.133 ± 0.042	24.68 ± 0.97	27.00 ± 0.41	27.01 ± 0.70
$\mu_\alpha \cos \delta$ (mas yr ⁻¹)	-53.138 ± 0.068	-57.6 ± 1.5	110.850 ± 0.040	112.39 ± 0.62	-9.948 ± 0.064	-10.9 ± 1.6	20.01 ± 0.75	29.3 ± 1.5
μ_δ (mas yr ⁻¹)	-98.328 ± 0.095	-95.2 ± 1.4	103.117 ± 0.045	103.47 ± 0.91	-74.913 ± 0.059	-73.2 ± 1.4	171.09 ± 0.77	173.0 ± 2.5
<i>Gaia</i> G (mag)	6.08969 ± 0.00046	20.070 ± 0.013	7.5035 ± 0.0016	19.3571 ± 0.0045	9.48280 ± 0.00018	20.4050 ± 0.0077	18.1977 ± 0.0042	20.3391 ± 0.0083
<i>Gaia</i> G _{BP} (mag)	5.5936 ± 0.0028	18.041 ± 0.066	6.9557 ± 0.0054	17.615 ± 0.032	8.79104 ± 0.00078	18.719 ± 0.037	16.520 ± 0.011	18.694 ± 0.024
PS1 <i>r</i> (mag)	...	...	7.7177 ± 0.0095	...	9.507 ± 0.064	21.14 ± 0.19	20.334 ± 0.015	21.693 ± 0.044
PS1 <i>i</i> (mag)	...	18.81 ± 0.17	7.73 ± 0.22	18.474 ± 0.014	9.50 ± 0.24	19.959 ± 0.024	17.6724 ± 0.0027	19.8205 ± 0.0077
PS1 <i>z</i> (mag)	...	17.779 ± 0.029	7.4026 ± 0.0063	17.37 ± 0.14	9.848 ± 0.021	18.456 ± 0.013	16.2113 ± 0.0034	18.4309 ± 0.0076
PS1 <i>y</i> (mag)	...	16.302 ± 0.058	6.817 ± 0.022	16.1001 ± 0.0060	8.8370 ± 0.0010	17.482 ± 0.019	15.3240 ± 0.0043	17.4922 ± 0.0083
2MASS <i>J</i> (mag)	5.19 ± 0.26	15.416 ± 0.051 ^a	6.232 ± 0.020	> 13.663	7.922 ± 0.019	15.421 ± 0.062	13.433 ± 0.029	15.432 ± 0.054
2MASS <i>H</i> (mag)	4.700 ± 0.053	14.755 ± 0.082 ^a	5.855 ± 0.016	> 13.210	7.414 ± 0.044	14.535 ± 0.046	12.792 ± 0.035	14.598 ± 0.059
2MASS <i>K_s</i> (mag)	4.551 ± 0.020	14.142 ± 0.067 ^a	5.741 ± 0.020	13.021 ± 0.042 ^a	7.276 ± 0.018	14.085 ± 0.076	12.356 ± 0.028	13.901 ± 0.047
AllWISE W1 (mag)	4.56 ± 0.20 ^b	11.007 ± 0.021 ^c	5.76 ± 0.12 ^b	...	7.123 ± 0.035 ^b	13.641 ± 0.024 ^d	12.002 ± 0.023	13.540 ± 0.026
AllWISE W2 (mag)	4.417 ± 0.056 ^b	10.884 ± 0.021 ^c	5.580 ± 0.045 ^b	...	7.298 ± 0.019	13.406 ± 0.029 ^d	11.750 ± 0.022	13.291 ± 0.028
AllWISE W3 (mag)	4.569 ± 0.015 ^b	10.666 ± 0.092 ^c	5.667 ± 0.015 ^b	...	7.255 ± 0.017	> 12.581	11.29 ± 0.10	12.60 ± 0.36

Notes: Coordinates, parallax, and proper motion are from *Gaia* DR2. Separation and position angle are computed at the *Gaia* DR2 epoch (2015.5). Spectral types are assigned using SPLAT (see Section 3), except for HD 164507, V478 Lyr AB, CD-28 8692, and 2MASS J18392917+4424386, whose spectral types are taken from the literature. References: 1: Harlan & Taylor (1970); 2: Fekel (1988); 3: Uppgren et al. (1972); 4: Bardalez Gagliuffi et al. (2014). Notes on photometry: ^acontaminated by bright star; ^bsaturated; ^ccontaminated by diffraction spike; ^dcontaminated by bright star halo.

Table 2. Astrometry, photometry, and spectral types for the 2MASS J0139+8110 AB, 2MASS J2325+4608 AB, and LT UMa AB systems presented here.

	2MASS J0139+8110		2MASS J2325+4608		LT UMa	
	A	B	A	B	A	B
RA (hh:mm:ss.ss)	01:39:09.00	01:38:59.67	23:25:35.40	23:25:35.09	08:44:47.95	08:44:50.12
Dec. (dd:mm:ss.s)	+ 81:09:59.7	+ 81:10:07.9	+ 46:08:15.8	+ 46:08:09.2	+ 55:32:19.7	+ 55:32:12.3
Sep. (arcsec)		23.00		7.24		19.83
Sep. (au)		959		378		879
PA (deg)		290.87		205.89		111.89
Sp. type	L1	L2	M8 V	L2	K0 V	M9 V
ϖ (mas)	23.98 ± 0.23	24.74 ± 0.79	19.13 ± 0.48	20.3 ± 1.4	22.550 ± 0.033	22.00 ± 0.43
$\mu_\alpha \cos \delta$ (mas yr ⁻¹)	-4.25 ± 0.51	-5.3 ± 1.4	-52.19 ± 0.64	-61.2 ± 2.6	76.636 ± 0.053	77.90 ± 0.60
μ_δ (mas yr ⁻¹)	-26.61 ± 0.33	-26.8 ± 1.0	-34.00 ± 0.51	-40.4 ± 1.8	12.890 ± 0.050	14.88 ± 0.57
<i>Gaia</i> <i>G</i>	18.4012 ± 0.0023	20.2468 ± 0.0070	16.4411 ± 0.0039	20.829 ± 0.012	8.6719 ± 0.0006	19.2895 ± 0.0033
<i>Gaia</i> <i>G</i> _{RP}	16.760 ± 0.010	18.560 ± 0.027	14.8492 ± 0.0038	19.086 ± 0.052	8.1151 ± 0.0020	17.648 ± 0.016
PS1 <i>r</i>	20.473 ± 0.046	>20.031	17.7361 ± 0.0088	>21.68	7.003 ± 0.001	>17.26
PS1 <i>i</i>	17.801 ± 0.013	19.763 ± 0.066	15.6181 ± 0.0035	20.301 ± 0.027	9.149 ± 0.030	18.616 ± 0.028
PS1 <i>z</i>	16.4260 ± 0.0077	18.325 ± 0.020	14.6096 ± 0.0040	18.847 ± 0.016	...	17.231 ± 0.013
PS1 <i>y</i>	15.6106 ± 0.0067	17.327 ± 0.017	14.0252 ± 0.0029	17.806 ± 0.019	9.475 ± 0.001	16.333 ± 0.018
2MASS <i>J</i>	13.891 ± 0.028	15.239 ± 0.046	12.561 ± 0.020	15.868 ± 0.070	7.458 ± 0.018	14.704 ± 0.035^a
2MASS <i>H</i>	13.233 ± 0.038	14.400 ± 0.049	11.955 ± 0.021	14.783 ± 0.059	7.124 ± 0.051	13.951 ± 0.043^a
2MASS <i>K_s</i>	12.829 ± 0.030	13.896 ± 0.053	11.573 ± 0.018	14.348 ± 0.076	7.016 ± 0.026	13.491 ± 0.024^a
AllWISE W1	12.381 ± 0.022	13.419 ± 0.024	11.387 ± 0.023	13.693 ± 0.080	6.927 ± 0.051^b	...
AllWISE W2	12.125 ± 0.023	13.109 ± 0.027	11.172 ± 0.021	13.493 ± 0.077	7.007 ± 0.020^b	...
AllWISE W3	11.64 ± 0.19	12.76 ± 0.46	10.90 ± 0.11	>11.946	6.985 ± 0.017	...

Notes: Coordinates, parallax and proper motion are from *Gaia* DR2. Separation and position angle are computed at the *Gaia* DR2 epoch (2015.5). Spectral types are assigned using SPLAT (see Section 3), except for LT UMa A, whose spectral types is taken from Strassmeier et al. (2000). Notes on photometry: ^acontaminated by bright star; ^bsaturated;.

online tool¹) for telluric correction after each target, matching the airmass of observation as closely as possible.

The data were reduced using a modified version of the IDL package SPEXTOOL (Cushing, Vacca & Rayner 2004). The program applies basic calibration (dark subtraction and flat fielding), then pairwise subtracts the images to remove sky background. The individual orders of the echelle spectra are traced and extracted, and wavelength calibration is achieved using the numerous OH sky lines. The individual orders are corrected for telluric absorption and flux calibrated using the observed telluric standard star, chosen to match the Vega spectrum used as template in SPEXTOOL. The individual orders are then merged, using their overlap to determine flux adjustments when needed. The reduced spectra are presented in Figs 2–4.

We assigned a spectral type to our targets via standard template-matching using the `classifyByStandard` routine in the PYTHON package “The SpeX Prism Library Analysis Toolkit”² (SPLAT; Burgasser et al. 2016). The code interpolates the templates to the same wavelength grid of the observed spectra, and then minimizes the χ^2 of the fit, treating the scaling between the flux-calibrated target and the normalized templates as a free parameter of the fit. The `classifyByStandard` routine offers the possibility to classify objects by fitting the full spectrum, as well as by fitting only the *J* band, following the prescriptions of Kirkpatrick et al. (2010). The spectral types obtained with the two methods agree to within ± 1 subtype, with the exception of CD-28 8692 B and 2MASS J0139+8110 A. We discuss the discrepancies and our

adopted classification in Sections 4.3 and 4.5. We used the standard M, L, and T templates defined in Burgasser et al. (2006) and Kirkpatrick et al. (2010), except in the case of V478 Lyr C, where standard templates gave poor fits. Further details on the spectral typing for this source are given in Section 4.2. The results from template matching are presented in Figs 2–4, and the assigned spectral types are listed in Tables 1 and 2.

4 NOTES ON INDIVIDUAL SYSTEMS

4.1 HD 164507 AB

The primary is a very well-characterized G5 IV star that is included in the catalogue of RV standards for *Gaia* (Soubiran et al. 2013). Several independent estimates of the atmospheric and evolutionary parameters for this subgiant can be found in the literature, and here we briefly summarize those based on high-resolution spectroscopy only.

Valenti & Fischer (2005) obtained *R* $\sim 70\,000$ spectroscopy for HD 164507 using the High-Resolution Echelle Spectrometer (HIRES) on the 10 m telescope at Keck Observatory (Vogt et al. 1994). They derived atmospheric parameters using version 2.1 of the software package Spectroscopy Made Easy (SME; Valenti & Piskunov 1996) and the atmospheric models by Kurucz (1992). Mass and age for the star were then derived using the *Y*² isochrones (Demarque et al. 2004). Takeda et al. (2007) and Maldonado, Villaver & Eiroa (2013) derived independent age and mass using the atmospheric parameters from Valenti & Fischer (2005). Takeda et al. (2007) employed the Yale Rotational Evolution Code (YREC) in its non-rotating mode (Demarque et al. 2008) to generate their set of isochrones, while Maldonado et al. (2013) used the Valenti &

¹<https://www.gemini.edu/sciops/instruments/nearir-resources/spectroscopic-standards-telluric-standard-search>

²<http://pono.ucsd.edu/~adam/browndwarfs/splat>

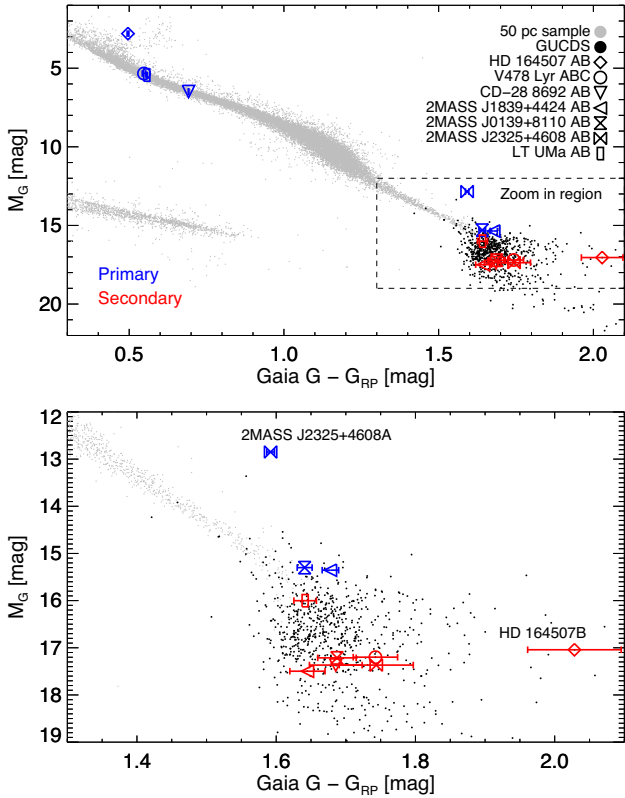


Figure 1. Colour–magnitude diagrams depicting the full stellar sequence (top) and a zoom into the UCDs region (bottom). The small grey points are stars in *Gaia* DR2 nominally within 50 pc, selected using the criteria described in appendix C of Lindegren et al. (2018). Black points are the UCDs identified in *Gaia* DR2 by GUCDS II. The seven systems presented here are plotted with different symbols, with the primary in each system plotted in blue and the companion in red. Vertical error bars are typically smaller than the symbols. Detailed analysis of individual systems can be found in Section 4.

Fischer (2005) spectroscopic T_{eff} and metallicity together with *Hipparcos* data as inputs for PARAM³ (da Silva et al. 2006) to derive age and mass for HD 164507.

Jofré et al. (2015) used high-resolution spectroscopy from the Spectrographe pour l’Observation des Phénomènes des Intérieurs stellaires et des Exoplanètes (SOPHIE) on the 1.93 m telescope at the Observatoire de Haute-Provence (Perruchot et al. 2008). The fundamental stellar parameters (T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$, and ξ_t) were computed homogeneously using the FUNDPAR code (Saffe 2011). The chemical abundances of 14 elements (Na, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Mn, Co, Ni, Zn, and Ba) were obtained using the 2009 version of the MOOG⁴ code (Snedden 1973). Rotational velocities were derived from the full width at half-maximum of isolated Fe lines. Again, mass and age were derived using PARAM.

Niedzielski et al. (2016) used the High Resolution Spectrograph (Tull 1998) on the Hobby-Eberly Telescope. The T_{eff} , $\log g$, ξ_t , and $[\text{Fe}/\text{H}]$ were obtained from the measured equivalent width of neutral and ionized iron absorption lines, with the TGVIT code (Takeda, Ohkubo & Sadakane 2002; Takeda et al. 2005). The stellar mass and age were determined using a Bayesian method described in Adam-

³<http://stev.oapd.inaf.it/cgi-bin/param.1.1>

⁴<https://www.as.utexas.edu/~chris/moog.html>

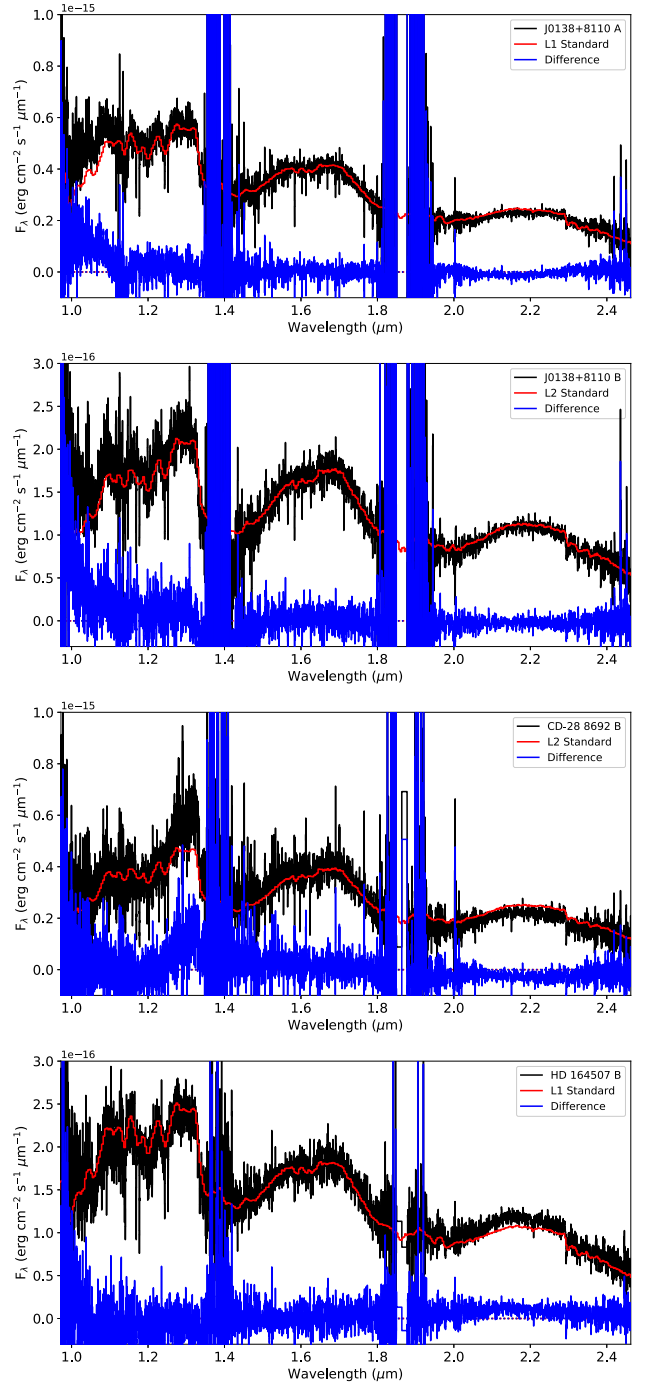


Figure 2. Spectral classification of the four UCD companions to GK stars observed with TripleSpec. In each panel, we show the target spectrum (black), the best-fitting template from the SpeX Prism library (red) and the difference between the two (blue). Spectral typing is done with SPLAT (Burgasser et al. 2016).

czyk, Deka-Szymankiewicz & Niedzielski (2016), with theoretical stellar models from Bressan et al. (2012). Deka-Szymankiewicz et al. (2018) updated the age and mass derived by Niedzielski et al. (2016) using the *Gaia* DR2 parallax.

Luck (2017) used spectra from The McDonald Observatory 2.1 m Telescope and Sandiford Cassegrain Echelle Spectrograph (McCarthy et al. 1993). Abundances and ξ_t were calculated using

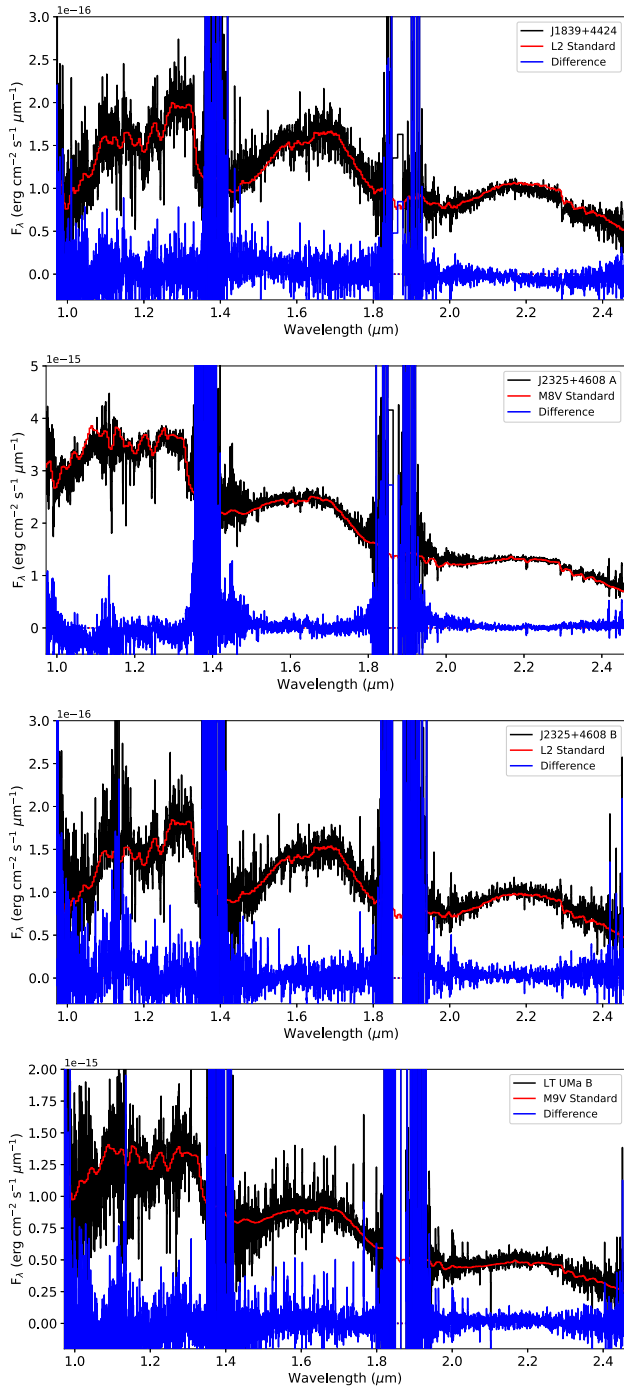


Figure 3. Same as Fig. 2, but for 2MASS J18392740+4424510, 2MASS J23253550+4608163, 2MASS J23253519 + 4608098, and LT UMa B.

measured equivalent widths and plane-parallel MARCS model atmospheres (Gustafsson et al. 2008), while T_{eff} and $\log g$ were computed from broad-band photometry and the photometric calibration of Casagrande et al. (2010). Finally, Luck (2017) determined mass and age using various sets of isochrones from Bertelli et al. (1994), Demarque et al. (2004), Dotter et al. (2008), and the 2016 version of the Bag of Stellar Tracks and Isochrones (BaSTI; Pietrinferni et al. 2004).

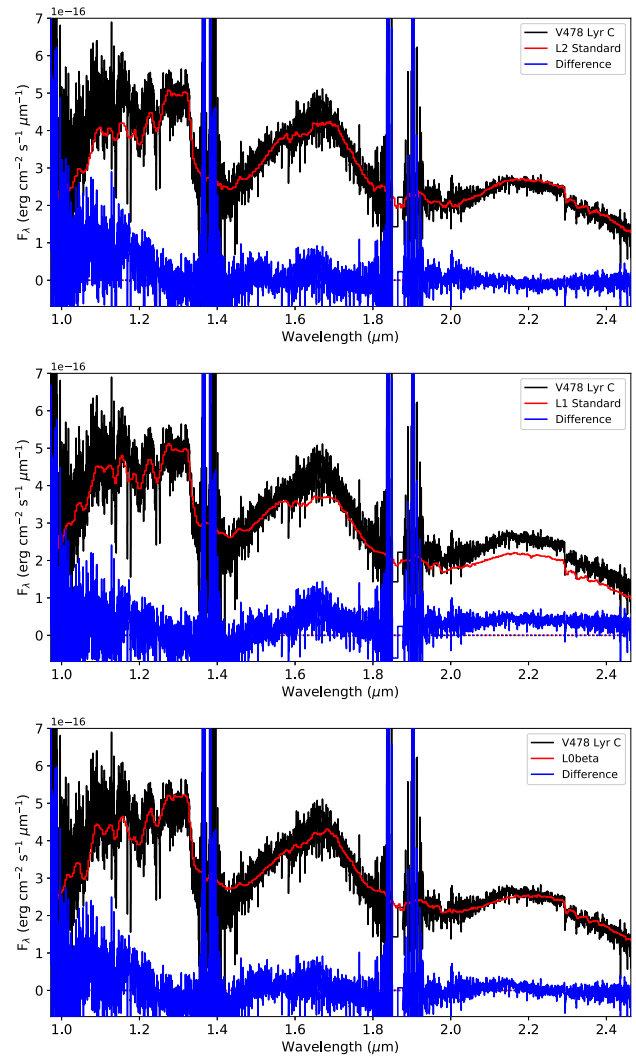


Figure 4. Spectral classification for V478 Lyr C. The top panel shows the best-fitting standard template fitting the whole spectrum, the middle panel shows the best-fitting standard template using the Kirkpatrick et al. (2010) method, while the bottom panel shows the best-fitting INT-G template (defined in Allers & Liu 2013). The colour-coding of spectra is the same as Fig. 2.

Finally, *Gaia* DR2 quotes $T_{\text{eff}} = 5560^{+115}_{-62}$ K (see Andrae et al. 2018, for details on how *Gaia* DR2 atmospheric parameters are derived), and the best-fitting template used for radial velocity (RV) measurement has $T_{\text{eff}} = 5500$ K, $\log g = 3.5$, and $[\text{Fe}/\text{H}] = +0.2$ dex (Sartoretti et al. 2018), all in good agreement with the literature values.

The atmospheric parameters discussed above are listed in Table 3. The values derived are in general agreement with each other, and in particular point towards a slightly supersolar metallicity ($[\text{Fe}/\text{H}] = 0.03\text{--}0.19$ dex), and an age for the system in the range 3.0–5.9 Gyr.

More accurate age constraints on this star will be provided by *TESS* (Ricker et al. 2015) via gyrochronology, making this system an exquisite benchmark for UCD models and retrieval codes testing (Line et al. 2015; Burningham et al. 2017, 2013).

The L1 companion, HD 164507 B, is an outlier in the colour–magnitude diagram of Fig. 1. With a $G - G_{RP}$ colour of

Table 3. Summary of atmospheric and evolutionary parameters for HD 164507 A.

Reference	T_{eff} (K)	$\log g$ (cm s^{-2})	[Fe/H] (dex)	ξ_t (km s^{-1})	Instrument	$v \sin i$ (km s^{-1})	Age (Gyr)	Mass (M_{\odot})
1	5650 ± 40	3.93 ± 0.06	0.19 ± 0.03	...	HIRES	2.9 ± 0.5	$4.2^{+1.7}_{-1.2}$	$1.36^{+0.17}_{-0.15}$
2	...	$3.83^{+0.03}_{-0.02}$	...	...	...	...	$4.04^{+0.2}_{-0.4}$	$1.328^{+0.048}_{-0.018}$
3	...	3.78 ± 0.02	...	...	...	...	3.67 ± 0.13	1.32 ± 0.02
4	5580 ± 20	3.98 ± 0.01	0.12 ± 0.02	1.08 ± 0.01	SOPHIE	1.02 ± 0.23	3.55 ± 0.19	1.33 ± 0.03
5,6	5534 ± 5	3.66 ± 0.02	0.13 ± 0.01	1.04 ± 0.04	HRS	2.28 ± 0.64	$3.162^{+0.015}_{-0.014}$	1.440 ± 0.004
7	5540 ± 60	3.72	0.03 ± 0.07	1.54	Sandiford	5.0	$3.20\text{--}5.32$	$1.17\text{--}1.37$
8,9	5560^{+110}_{-60}	3.5	0.2	...	<i>Gaia</i>	...	...	...

Notes: References: 1: Valenti & Fischer (2005); 2: Takeda et al. (2007); 3: Maldonado et al. (2013); 4: Jofré et al. (2015); 5: Niedzielski et al. (2016); 6: Deka-Szymankiewicz et al. (2018); 7: Luck (2017); 8: Andrae et al. (2018); and 9: Sartoretti et al. (2018).

2.028 ± 0.067 mag, it is among the reddest UCDs in the *Gaia* sample. Objects with similar $G - G_{RP}$ colour are found in GUCDS II to be either tight binaries or suspect tight binaries. The red $G - G_{RP}$ colour in this case would be due to the fact that G_{RP} (and G_{BP}) magnitudes are determined by integrating the G_{RP} fluxes in a 3.5×2.1 arcsec² window, and there is currently no treatment of multiple sources in the same window in *Gaia* DR2 (Evans et al. 2018). As we expect the unseen secondary to be cooler an excess in G_{RP} for close binary systems is expected. However, there is no evidence for binarity of HD 164507 B. The source is not resolved by *Gaia*, and the goodness-of-fit and astrometric excess noise reported in *Gaia* DR2 (2.7359 and 2.108 mas, respectively) are both consistent with the mean values for UCDs found in GUCDS II (5.2 ± 2.6 and 2.2 ± 1.2 mas, respectively). The primary has higher-than-solar metallicity ($0.03 < [\text{Fe}/\text{H}] < 0.19$ dex, see Section 4.1), and higher metallicity UCDs are expected to have redder than average colours because of the enhanced dust content in their photosphere (e.g. Looper et al. 2008; Marocco et al. 2014). However the near-IR spectrum of HD 164507 B does not show obvious peculiarities (see Fig. 2). Finally, youth is also typically associated with redder-than-usual colours (see e.g. Faherty et al. 2016), but young and suspected young objects in GUCDS II form a relatively tight sequence with $1.6 \lesssim G - G_{RP} \lesssim 1.8$ mag, and the age of the system rules out youth as a cause. Optical spectroscopy for this UCD is desirable to shed light on its nature.

We derive T_{eff} for the companion using the Filippazzo et al. (2015) spectral type to T_{eff} polynomial relation, and obtain $T_{\text{eff}} = 2100 \pm 29$ K. Linear interpolation of the BT-Settl isochrones⁵ for solar and supersolar metallicity ($[\text{Fe}/\text{H}] = +0.5$ dex) in the age range 3.0–5.9 Gyr, and for $T_{\text{eff}} = 2100 \pm 29$ K, gives a mass for the companion in the range 50–77 M_{Jup} , at or below the hydrogen burning limit.

To compute the bolometric luminosity (L_{bol}), we need to determine a bolometric correction, since our TripleSpec spectrum only covers the $1.0 < \lambda < 2.4$ μm range. We did this by fitting the TripleSpec spectrum with the BT-Settl atmospheric models (Allard, Homeier & Freytag 2012b) with the fitting technique developed by Cushing et al. (2008). The models cover the T_{eff} space in steps of 50 K, the $\log g$ space in steps of 0.5 dex, and the $[\text{Fe}/\text{H}]$ space in steps of 0.5 dex.

We flux calibrated the target’s spectrum using the measured 2MASS J -band magnitude, and then allowed the scaling factor between the flux-calibrated spectrum and the models to be a parameter of the fit. The best-fitting scaling factor gave us a

measurement of the radius (R) of the target via the simple geometric dilution factor $(R/d)^2$. We restricted the range of models to be considered for fitting to the ± 200 K range around the predicted T_{eff} of 2100 K and the metallicity to be within ± 0.5 dex of the metallicity of the primary, for which we chose the mid-point of the values quoted in the literature, i.e. 0.11 dex.

We used the scaled best-fitting atmospheric model to complete the TripleSpec spectrum at long and short wavelength ($\lambda < 1$ μm and $\lambda > 2.4$ μm). L_{bol} was then computed by summing the flux density over the full model + TripleSpec spectrum, and multiplying it by $4\pi d^2$. The uncertainty on L_{bol} was computed by propagating the uncertainty on the measured spectrum, as well as the uncertainty on the 2MASS magnitude used for flux calibration, and the uncertainty on the distance.

The best-fitting model for HD 164507 B has $T_{\text{eff}} = 2300$ K, $\log g = 5.0$, and $[\text{Fe}/\text{H}] = +0.5$ dex. The radius corresponding to the best-fitting scale factor is $0.88 R_{\text{Jup}}$, and the bolometric luminosity is $\log_{10}(L_{\text{bol}}/L_{\odot}) = -3.144^{+0.039}_{-0.043}$. Approximately 17 per cent of the bolometric luminosity reported here is outside of the TripleSpec wavelength range (1.0–2.4 μm). This fraction decreases with spectral type, as the contribution from the optical portion of the spectral energy distribution (SED) collapses, while the longer wavelength flux does not increase significantly. The model-dependent fraction of L_{bol} approaches ~ 40 per cent for the late-Ms in our sample, and decreases down to ~ 8 per cent for the L2s. The best-fitting model for HD 164507 B is shown in Fig. 5. The overall fit is poor: (i) the model has a triangular H band, while the target has a much flatter H -band spectrum; (ii) the alkali lines in the J band are much too shallow in the model compared to the observed ones; (iii) the K -band spectrum in the model is too flat, and (iv) the overall spectrum is too blue compared to our target. The best-fitting T_{eff} is 200 K warmer than the prediction from the Filippazzo et al. (2015) polynomial.

4.2 V478 Lyr ABC

The primary is a chromospherically active G8 V single-lined spectroscopic binary with a period of about 2.13 d (Fekel 1988). This star was found to have strong ultraviolet (UV) emission features and a filled-in $H\alpha$ absorption line that is variable in strength. Therefore, Fekel (1988) classified it as an early-type BY Draconis system. The secondary had its mass estimated to be about $0.3 M_{\odot}$ and to be probably an M2–M3 dwarf. The inclination of the system was measured to be $67 \pm 12^{\circ}$. The lithium abundance of the G8 dwarf, estimated from the equivalent width of the Li I 6707.8 Å line (47 mÅ), led Fekel (1988) to propose an age for the system that is

⁵<https://phoenix.ens-lyon.fr/Grids/BT-Settl/CIFIST2011/ISOCHRONES/>

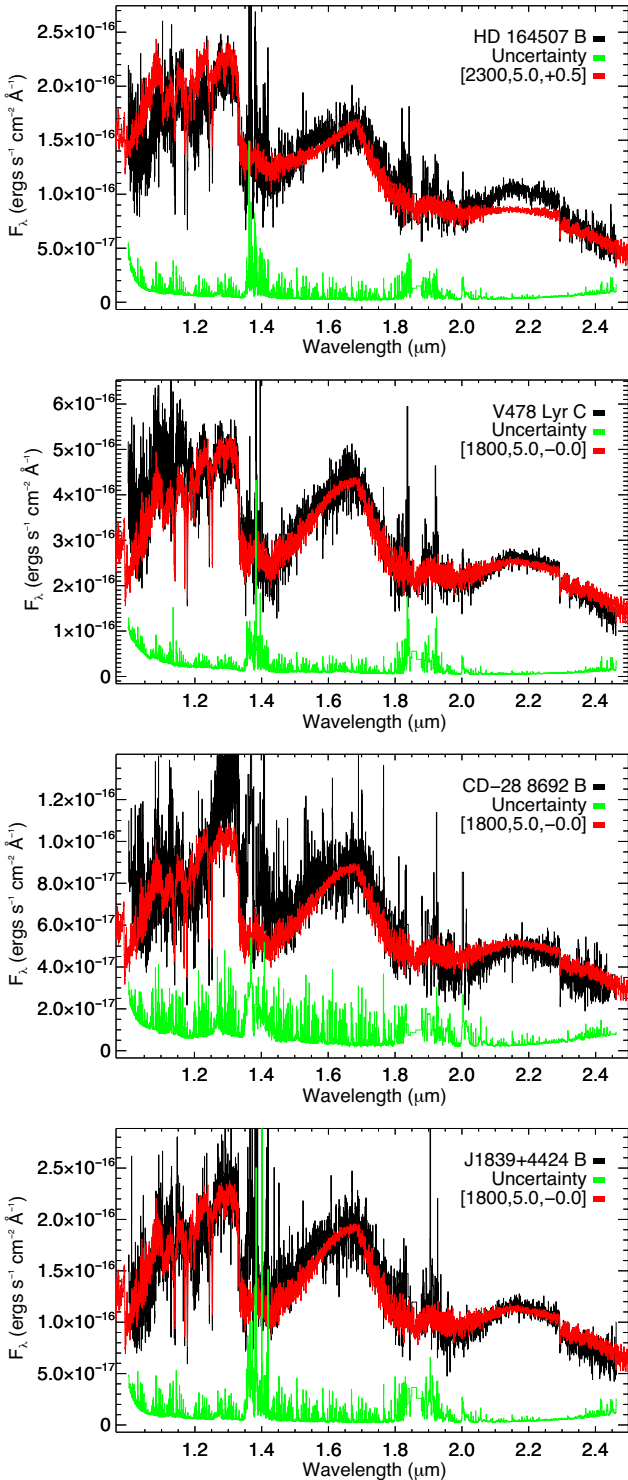


Figure 5. The spectra of HD 164507 B, V478 Lyr C, CD-28 8692 B, and 2MASS J18392740+4424510 (black) with the measured flux uncertainty (green) and the best-fitting BT-Settl atmospheric model (red). The best-fitting T_{eff} , $\log g$, and $[\text{Fe}/\text{H}]$ are indicated on the plot. For details on the fitting procedure, see Sections 4.1–4.7.

somewhat less than that of the Hyades cluster (680 Myr; Gossage et al. 2018).

Using the BANYAN Σ online tool, the *Gaia* DR2 astrometry, and the mean RV from Nordström et al. (2004), we find a probability of

0 per cent for the object to be a member of any of the young moving groups considered in BANYAN Σ (including the Hyades).

Nevertheless, the UCD companion, dubbed V478 Lyr C, shows a somewhat triangular *H*-band spectrum, a feature previously associated with youth (Lucas et al. 2001; Allers & Liu 2013). Gravity-sensitive spectral indices and pseudo-equivalent width defined in Allers & Liu (2013) however lead to a L1 field surface gravity (FLD-G) classification for the companion. Intermediate surface gravity (INT-G), and very-low surface gravity (VL-G) objects in the Allers & Liu (2013) sample have typical age < 200 Myr and, according to a more recent study conducted by Martin et al. (2017), the reliability of the gravity classification drops significantly for objects with age > 100 Myr. On the other hand, the L1 companion to the young A3V star β Circini has a flat *H*-band spectrum (and no low gravity features, see Smith et al. 2015). The age of the β Circini system has been estimated to be in the 370–500 Myr range. We would therefore expect the V478 Lyr system to be somewhat younger than the β Circini system, but likely older than ~ 100 Myr.

Spectral typing via standard template matching leads to an L2 type. However the fit in Fig. 4 is poor, with the standard not only failing to match the *H*-band shape, but also underestimating the flux at the blue end of the spectrum (up to $\sim 1.2 \mu\text{m}$). Using the Kirkpatrick et al. (2010) method, i.e. fitting only the 0.9–1.4 μm range, the best-fitting template is the L1 standard, but the target shows flux excess at the longer wavelength, as expected for a low surface gravity object.

If we fit V478 Lyr C with the low gravity templates defined in Allers & Liu (2013), the best fit is the L0 β standard. The fit to the *H* band is much more accurate, and the flux in the *J* band is less underestimated, but at the same time the fit to the H₂O band at $\sim 1.4 \mu\text{m}$ is poorer. Given all of the above, we assign V478 Lyr C a spectral type of L1.

Filippazzo et al. (2015) derived an M_H to T_{eff} polynomial relation for young objects, but the available near-IR photometry for V478 Lyr C is heavily contaminated by the parent star (at $\rho \sim 17$ arcsec). We computed a synthetic *H*-band magnitude using our flux-calibrated TripleSpec spectrum and the 2MASS *H*-band response curve (Cohen, Wheaton & Megeath 2003). We estimated the accuracy of our synthetic *H* magnitude by comparing the synthetic magnitudes obtained for the other objects observed as part of our TripleSpec run, against their measured 2MASS *H* (for all except HD 164507 B, since its photometry is also contaminated). The mean offset between our synthetic magnitudes and the measured ones is -0.007 mag and the 1σ dispersion around the mean is 0.44 mag. We therefore adopted 13.74 ± 0.44 mag as our synthetic measurement, and obtain $T_{\text{eff}} = 1740 \pm 130$ K for V478 Lyr C as a result. Linear interpolation of the BT-Settl isochrones for solar metallicity in the age range 0.10–0.37 Gyr gives a mass for this object in the range 10–28 M_{Jup} , straddling the deuterium fusion mass limit.

We determined L_{bol} for V478 Lyr C following the same procedure described in Section 4.1. The best-fitting model has $T_{\text{eff}} = 1800$ K, $\log g = 5.0$, and solar metallicity. The $\log g = 5.0$ is somewhat higher than one might expect, given the age of the system, and the fact that this object shows signs of youth. The radius resulting from the best-fitting scaling factor is $1.31 R_{\text{Jup}}$ and the bolometric luminosity is $\log_{10}(L_{\text{bol}}/L_{\odot}) = -3.33^{+0.26}_{-0.78}$. The best-fitting model can be seen in Fig. 5. The overall fit is good, with the model only slightly underpredicting the flux at the shortest wavelength ($\lambda < 1.2 \mu\text{m}$) but that is the region of lowest signal-to-noise-ratio.

Oh et al. (2017) found the SB1 primary to form a very wide comoving pair with the G6V HD 171067, with a projected sep-

aration of ~ 8 pc. The Oh et al. (2017) analysis however did not take into account RV. The measured system RV for V478 Lyr AB is -25.2 ± 4.8 km s $^{-1}$ (Nordström et al. 2004), and is discrepant from the RV of HD 171067 (-46.197 ± 0.002 km s $^{-1}$; Soubiran et al. 2013). As a result, the G6V is unlikely to be associated with the V478 Lyr triple system.

V478 Lyr ABC joins the rank of triple systems consisting of a spectroscopic binary with a wide, low-mass tertiary component (see Allen et al. 2012, and references therein). These systems are precious for testing formation simulations of very close separation binaries, which require a mechanism to draw angular momentum away from an already close pair of objects. One proposed mechanism is through three-body interactions with cool dwarfs (see e.g. Sterzik & Durisen 2003; Delgado-Donate et al. 2004; Umbreit et al. 2005), and a key observable to test such scenario is the fraction of tight spectroscopic binaries that have a wide additional companion. Towards this goal, V478 Lyr AB was among the stars targeted by Allen et al. (2012), who conducted a deep near-IR survey looking for low-mass tertiary components around 118 known spectroscopic binaries within 30 pc of the Sun. However, V478 Lyr C was missed probably because of the combination of its tight angular separation from the binary (17.05 arcsec, close to the Allen et al. 2012 survey limit of 10–15 arcsec), the large magnitude difference between SB1 primary and L dwarf companion, and the large contamination by reddened background sources resulting from its proximity to the Galactic plane ($b = 10.1^\circ$).

Finally, the estimated orbital period for this system is $\gtrsim 8000$ yr, despite this being the most favourable configuration among the seven systems presented here – i.e. a relatively massive primary, with a relatively tight separation, and assuming a face-on circular orbit. If instead we assume the wide L1: companion is coplanar with the SB1, i.e. that the inclination angle is $67 \pm 12^\circ$, then the orbital period would be ~ 9700 yr. In either case, no dynamical mass measurement is possible for the UCD. The other systems presented here have even longer estimated orbital periods.

4.3 CD-28 8692 AB

The primary is a slightly metal poor K5 V star. It has been monitored with the High Accuracy Radial velocity Planet Searcher (HARPS) for planets by Sousa et al. (2011), who found no evidence for RV variations. Sousa et al. (2011) also used the HARPS spectra to determine atmospheric parameters, and obtained $T_{\text{eff}} = 4799 \pm 90$ K, $\log g = 4.43 \pm 0.18$, and $[\text{Fe}/\text{H}] = -0.22 \pm 0.06$ dex. They then estimated a mass of $0.715 \pm 0.014 M_\odot$ for the star using the measured atmospheric parameters and the Padova isochrones. Adibekyan et al. (2012) used the atmospheric parameters estimated by Sousa et al. (2011) and the HARPS spectra to measure detailed abundances of 12 chemical species, with typical precision in the 0.035–0.260 dex range.

Later, Delgado Mena et al. (2015) used the HARPS data to estimate atmospheric parameters and combined them with the Li I abundance to infer an age of 4.48 Gyr for this star.

The *Gaia* DR2 effective temperature for this star is 4742_{-116}^{+138} K (Andrae et al. 2018), while the best-fitting template used for RV measurement has $T_{\text{eff}} = 4750$ K, $\log g = 4.5$, and $[\text{Fe}/\text{H}] = -0.2$ dex (Sartoretti et al. 2018). All *Gaia* DR2 values are in good agreement with the literature measurements.

The companion presented here is classified as L2, with a projected separation of 2026 au (50.91 arcsec). The L2 template is a good fit to the spectrum of the target, with the exception of a slightly suppressed *K* band (typical of metal-poor and high surface gravity

dwarfs; Burgasser et al. 2008; Zhang et al. 2017), and a flux excess at ~ 1.3 μm . Scatter in the strength of the ~ 1.3 μm peak among objects of a given spectral type has been observed before (Cruz et al. 2018). The Kirkpatrick et al. (2010) method yielded a very different classification of L6. While the L6 template does indeed provide a slightly better fit to the *J* band reducing the overluminosity at ~ 1.3 μm , the target is much bluer than the L6 standard at longer wavelength. Low metallicity L dwarfs are indeed slightly bluer compared to their solar metallicity counterparts, but this system is only slightly metal poor, and therefore a large suppression of the *H*- and *K*-band flux is unlikely. Moreover, the absolute *G* magnitude for CD-28 8692 B is 17.406 ± 0.004 mag, which is consistent with the median value for L2s (17.24 ± 0.41 mag; GUCDS II), but nearly two magnitudes overluminous compared to typical L6s (19.25 ± 0.60 mag; GUCDS II). Therefore, we retain a classification of L2 for this object.

Somewhat counterintuitively, the spectral indices for CD-28 8692 B are consistent with an INT-G classification. This is unexpected, since a relatively old, metal-poor object should exhibit surface gravity typical of standard field L dwarfs, or at most slightly higher. The transition between INT-G and FLD-G however is not very sharp, and scatter around the dividing line has been previously noted (Martin et al. 2017). The unusual metallicity of the CD-28 8692 AB system further affects the reliability of the gravity classification, as first noticed by Aganze et al. (2016) for the M9.5 companion to the metal-poor M1 V GJ 660.1A ($[\text{Fe}/\text{H}] = -0.63 \pm 0.06$ dex). We therefore conclude that our INT-G classification for CD-28 8692 B is incorrect.

The solar metallicity BT-Settl isochrones at $T_{\text{eff}} = 1960 \pm 29$ K (as given by the Filippazzo et al. 2015 polynomial relations) and age = 4.48 Gyr gives a mass of $\sim 70 M_{\text{Jup}}$. Although the system is slightly metal poor, we cannot use the publicly available BT-Settl isochrones for low metallicity ($[\text{Fe}/\text{H}] = -0.5$ dex), since they do not extend below $75 M_{\text{Jup}}$ and $T_{\text{eff}} \sim 3000$ K.

We determined L_{bol} for CD-28 8692 B following the same procedure described in Section 4.1. The best-fitting model has $T_{\text{eff}} = 1800$ K, $\log g = 5.0$, and solar metallicity. We determine a radius of $0.87 R_{\text{Jup}}$, and $\log_{10}(L_{\text{bol}}/L_\odot) = -3.688_{-0.053}^{+0.047}$. The best-fitting model is shown in Fig. 5. The model fit is of good quality, the main discrepancies being in the blue wing of the *H* band (the model underpredicting the observed flux) and at ~ 1.3 μm , where the model does not correctly reproduce the sharp observed peak (see above).

4.4 2MASS J23253550+4608163 + 2MASS J23253519+4608098

2MASS J23253550+4608163 is overluminous compared to objects of similar $G - G_{\text{RP}}$ colour and spectral type. Typical M8 dwarfs have $M_G = 15.24 \pm 0.63$ mag (see GUCDS II), while our target has $M_G = 12.850 \pm 0.004$ mag.⁶ The overluminosity cannot be explained by unresolved binarity alone, since an equal-mass binary would at most be 0.75 mag overluminous, while the target is almost 2.4 mag overluminous. Young objects can also be redder and overluminous compared to field-age objects. However, 2MASS J23253550+4608163 does not show any indication of youth in its near-IR spectrum (see Fig. 3, middle panel) and its kinematics are inconsistent with membership to any of the

⁶ Absolute magnitudes throughout this paper are computed using $1/\varpi$ as the distance, since for all targets $\varpi/\sigma_\varpi > 10$.

young moving groups using the BANYAN Σ online tool⁷ (Gagné et al. 2018). Contamination by a background object could be another possibility, and this source is indeed flagged as duplicate (duplicated_source = 1), however the background object would need to have the $G - G_{RP}$ colour of a late-M dwarf, since the $G - G_{RP}$ of 2MASS J23253550+4608163 is in line with the median colour of M8 dwarfs (1.592 ± 0.005 mag versus 1.61 ± 0.95 mag, see GUCDS II). External photometry from 2MASS, PanSTARRS-1, and AllWISE does not show evidence of contamination nor peculiar colours, but all absolute magnitudes are similarly overluminous when compared with M8 dwarfs.

An indication of possible problems is the relatively large goodness-of-fit (astrometric_gof_all) of 132 (cf. the mean value of 5.2 ± 2.6 for objects in GUCDS II), which may indicate that the parallax for this source is spuriously large. The companion, 2MASS J23253519+4608098, does not show any sign of peculiarity, neither photometric nor spectroscopic. This could therefore be an unfortunate case of chance alignment, with 2MASS J23253550+4608163 being a background M dwarf whose spurious astrometry is consistent, by chance, with being a companion to 2MASS J23253519+4608098. The astrometry for 2MASS J23253519+4608098 would instead be correct. The chance of such an unfortunate alignment is however extremely low, given the tight separation of the pair on the sky (7.24 arcsec). We therefore have no conclusive explanation for the overluminosity of this object.

We determined L_{bol} for both components of this system following the same procedure described in Section 4.1. The best-fitting model for the A component has $T_{\text{eff}} = 2400$ K, $\log g = 5.0$, and $[\text{Fe}/\text{H}] = +0.5$ dex. The radius is $3.14 R_{\text{Jup}}$ (cf. model-predicted value of $2.33 R_{\text{Jup}}$), which is unusually large for an UCD, but probably a consequence of the overluminosity discussed above. The result is $\log_{10}(L_{\text{bol}}/L_{\odot}) = -1.928_{-0.027}^{+0.026}$.

The best-fitting model for the B component has $T_{\text{eff}} = 1800$ K, $\log g = 5.5$, and solar metallicity. The radius corresponding to the best-fitting scaling factor is $R = 1.39 R_{\text{Jup}}$ which is somewhat large for an object with this temperature and surface gravity (the BT-Settl models predict $R \sim 0.9 R_{\text{Jup}}$). The bolometric luminosity is $\log_{10}(L_{\text{bol}}/L_{\odot}) = -3.265_{-0.060}^{+0.053}$. The best-fitting models for both components are shown in Fig. 6. The fit to the spectrum of 2MASS J23253550+4608163 is overall poor. The model appears too blue compared to the observed spectrum with the flux at $\lambda < 1.3 \mu\text{m}$ being overestimated and the flux in the K band being underestimated. The shape of the H band is also poorly reproduced, with the model having a more pronounced peak, while the observed spectrum appears flatter. The fit to the L dwarf component, 2MASS J23253519+4608098, is good, with the model only slightly underpredicting the flux at $\lambda < 1.25 \mu\text{m}$.

4.5 2MASS J01390902+8110003 + 2MASS J01385969+8110084

With a projected separation of 959 au, this system is to our knowledge the widest L + L dwarf binary known to date.

The primary is an L1 based on the template fitting to the whole spectrum, while a fit to the J band alone results in a significantly earlier spectral type, M8. The discrepancy is mostly driven by the slightly overluminous blue end of the TripleSpec spectrum ($\lambda < 1.1 \mu\text{m}$, see Fig. 2). The L1 standard gives a good fit to the overall spectrum except for this wavelength range, which is however also

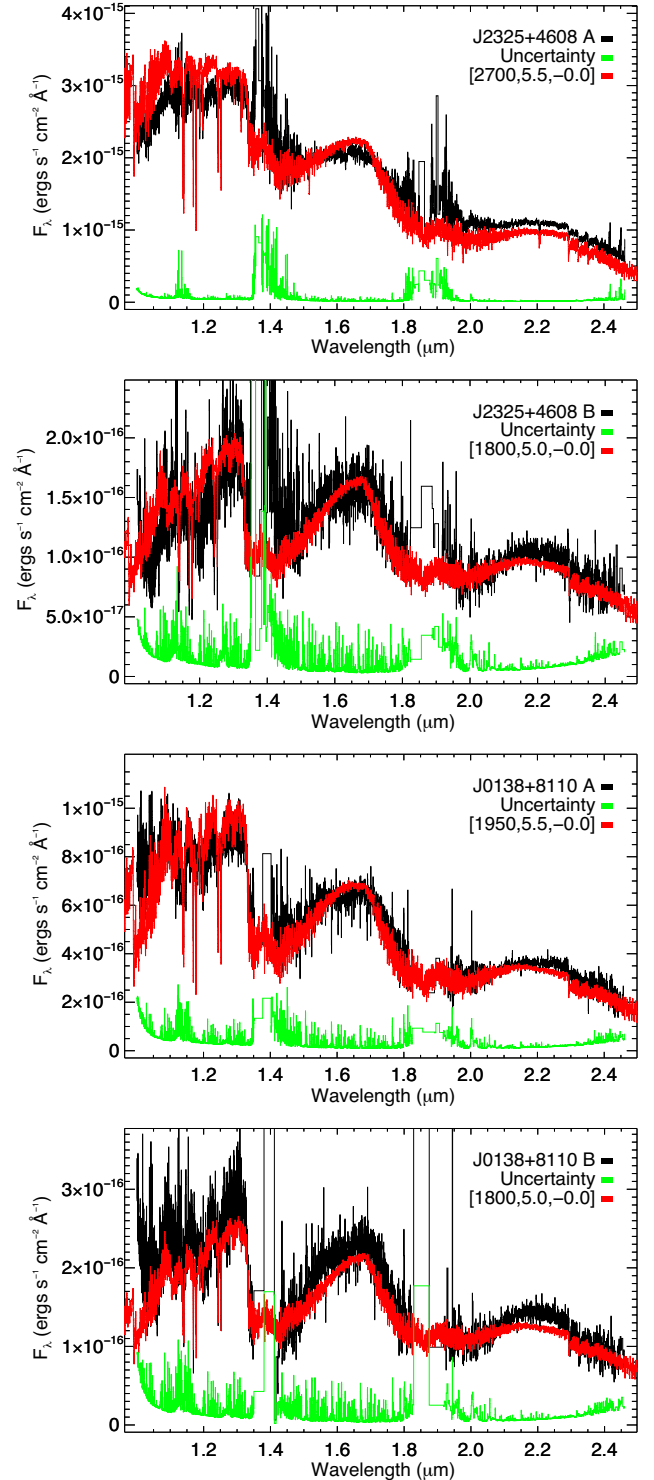


Figure 6. Same as Fig. 5, but for 2MASS J23253550+4608163, 2MASS J23253519+4608098, 2MASS J01390902+8110003, and 2MASS J01385969 + 8110084.

the lowest signal-to-noise-ratio portion of the spectrum. On the other hand, the M8 template reproduces better this part of the spectrum, but starts to diverge from the observations at wavelength longer than $\sim 1.3 \mu\text{m}$, with the target being overall redder than the template. While in principle this could be evidence of youth, the morphology

⁷<http://www.exoplanetes.umontreal.ca/banyan/banyansigma.php>

of the H band, and the depth of the Na I and K I absorption lines suggest that the object is not particularly young. We assume a spectral type of L1 for this object in the rest of the analysis. The companion is classified as L2 by both methods.

Various authors have focused on the identification of wide low-mass binaries. Recent examples include SLoWPoKES (Sloan Low-mass Wide Pairs Of Kinematically Equivalent Stars, Dhital et al. 2010; Baron et al. 2015; Gálvez-Ortiz et al. 2017). Extremely wide low-mass binaries do exist, with separations out to tens of thousands of au, and are found in young clusters and moving groups (see e.g. GUCDS II, Alonso-Floriano et al. 2015) as well as in the field (Dhital et al. 2010; Caballero 2012; Caballero & Montes 2012; Caballero et al. 2012). These systems are rare, with an estimated fraction of wide low-mass binaries in the field of 1–2 per cent (Burgasser, Dhital & West 2009). Their paucity may be explained via Galactic dynamical evolution, with subsequent stellar encounters in the Galactic disk progressively increasing the separation between the low-mass binary components, eventually leading to its dissolution (Weinberg, Shapiro & Wasserman 1987). This sets a hard lower limit on the binding energy (see e.g. Burgasser et al. 2003; Caballero 2009).

However rare, these systems pose a challenge to the formation models of low-mass stars and brown dwarfs. In particular, Kouwenhoven et al. (2010, 2011) argued that systems with separation > 1000 au are unlikely to have been formed as primordial binaries (since their orbital separation would be comparable to the size of an embedded cluster), but instead originated during the cluster dissolution process. Dhital et al. (2010) observed a bimodal binary separation (also observed by Kouwenhoven et al. 2010), suggesting the presence of two populations, one old and tightly bound, and another young and weakly bound, recently formed and unlikely to survive more than a few Gyr.

For us to determine how strongly bound this system is, we need to constrain the mass of the components. The spectra, presented in Fig. 2, do not present any obvious peculiarity, and both give a good fit to the standard templates. We can therefore reasonably assume that these two L dwarfs are of solar metallicity, and with age > 0.37 Gyr (following the same reasoning used in Section 4.2). We estimate the effective temperature for the two components using the Filippazzo et al. (2015) polynomial relation, and obtain 2100 ± 29 and 1960 ± 29 K for the L1 and L2, respectively. Given these temperatures, interpolation of the BT-Settl isochrones in the 0.37–13 Gyr range gives a mass of 44 – 82 and 42 – 80 M_{Jup} , respectively, corresponding to a total system mass in the 0.08 – 0.15 M_{\odot} range. The corresponding binding energy for the pair is $3 \times 10^{33} < |U_g^*| < 1 \times 10^{34}$ J, just above the $|U_g^*| > 10^{33}$ J limit proposed by Caballero (2009).

We can finally estimate how long the 2MASS J01390902+8110003 + 2MASS J01385969+8110084 system is likely to survive stellar encounters in the Galactic disc, using the method described in Dhital et al. (2010). Re-arranging their equation (18), and assuming a lower limit on the total mass for this system of 0.08 M_{\odot} , we find that the expected lifetime would be > 22 Gyr. Alternatively, we can compute the maximum separation for a binary of given total mass to remain bound for at least 10 Gyr, re-arranging equation (28) from Weinberg et al. (1987) and following their assumption of an average Galactic stellar density of 0.16 pc^{-3} , an average stellar mass of $0.7 M_{\odot}$, and a relative velocity for the stellar encounters of $\sim 20 \text{ km s}^{-1}$. We find the maximum separation for a system of total mass $> 0.08 M_{\odot}$ to be $> 1.5 \times 10^3$ au. The system is therefore bound.

We determined L_{bol} for both components of the system following the same procedure described in Section 4.1. The best-fitting model for component A has $T_{\text{eff}} = 1950$ K, $\log g = 5.5$, and solar metallicity. We determine a radius of $2.16 R_{\text{Jup}}$ and $\log_{10}(L_{\text{bol}}/L_{\odot}) = -2.753^{+0.029}_{-0.031}$. The radius is unusually large, and inconsistent with the model-predicted radius for an object of such atmospheric properties ($1.14 R_{\text{Jup}}$).

The best-fitting model for the B component has $T_{\text{eff}} = 1800$ K, $\log g = 5.0$, and solar metallicity. The resulting radius is $1.58 R_{\text{Jup}}$ and $\log_{10}(L_{\text{bol}}/L_{\odot}) = -3.158^{+0.034}_{-0.037}$. The radius is once again unusually large, and even more inconsistent with the model-predicted radius for an object of such atmospheric properties ($0.91 R_{\text{Jup}}$). The best-fitting models for both components can be seen in Fig. 6. The fit to the L1 (2MASS J01390902+8110003) is overall good, while the fit to the L2 (2MASS J01385969+8110084) is of slightly lower quality. Main discrepancies are an overall underestimated flux in the blue wing of the H band, as well as in the K band and at $\sim 1.3 \mu\text{m}$.

4.6 2MASS J18392917+4424386 + 2MASS J18392740+4424510

This is a very wide (811 au) M+L binary, akin to the 2MASS J01390902+8110003 + 2MASS J01385969+8110084 system.

The primary is the only previously known UCD discussed in this paper, and was classified M9 V using the NASA Infrared Telescope Facility (IRTF) SpeX spectroscopy in Bardalez Gagliuffi et al. (2014). The TripleSpec spectrum for the companion is presented in Fig. 2, and does not present any obvious peculiarity. We classify it as L2 via template matching.

Following the same method described above, we estimate the T_{eff} for the two components to be 2400 ± 29 and 1960 ± 29 K, respectively, leading to masses of 49 – 88 and 42 – 80 M_{Jup} . The binding energy of the system is therefore $4 \times 10^{33} < |U_g^*| < 1 \times 10^{34}$ J. The expected lifetime (computed using the same procedure described in Section 4.5) is > 28 Gyr and the separation limit $> 1.6 \times 10^3$ au. The system is therefore bound.

We determined L_{bol} for the L dwarf following the same procedure described in Section 4.1. The best-fitting model has $T_{\text{eff}} = 1800$ K, $\log g = 5.5$, and solar metallicity. We determine a radius of $1.19 R_{\text{Jup}}$ and $\log_{10}(L_{\text{bol}}/L_{\odot}) = -3.440^{+0.042}_{-0.046}$. The best-fitting model is presented in Fig. 5.

4.7 LT UMa AB

LT UMa is a variable star of BY Dra type, with an amplitude of 0.03 mag (no period listed) in The International Variable Star Index,⁸ based on 11 observations by Strassmeier et al. (2000).

The companion was first identified by Pinfield et al. (2006) based on motion and colour, but no spectroscopy was presented there. The Washington Double Star Catalog lists the pair as WDS J08448+5532. The spectral types are reported as ‘K0 III + L?’, following the primary classification presented in Yoss (1961) and the companion estimated spectral type derived in Pinfield et al. (2006). The primary was however reclassified as K0 V in Strassmeier et al. (2000) and Tsvetkov, Popov & Smirnov (2008).

Strassmeier et al. (2000) determined the effective temperature for LT UMa using the B and V magnitudes taken from the Tycho catalogue (Høg et al. 1997), and the $B - V$ calibration from

⁸<https://www.aavso.org/vsx/index.php>

Table 4. Spectral indices and pseudo-equivalent widths for HD 164507 B, V478 Lyr C, CD-28 8692 B, and LT UMa B.

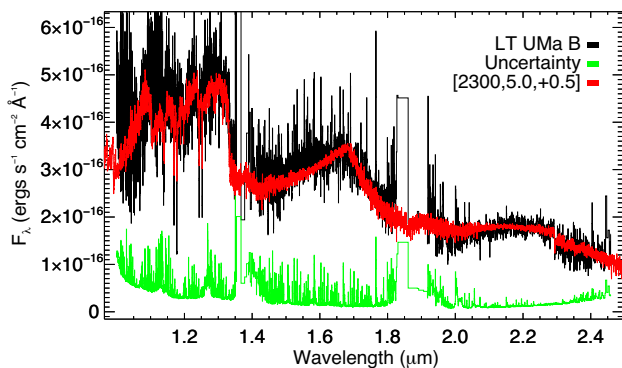
Index	HD 164507 B	V478 Lyr C	CD-28 8692 B	LT UMa B	Reference
H ₂ O	1.20 ± 0.01	1.23 ± 0.01	1.28 ± 0.03	1.16 ± 0.02	1
H ₂ OD	0.915 ± 0.008	0.958 ± 0.006	0.88 ± 0.02	1.07 ± 0.02	2
H ₂ O-1	0.626 ± 0.004	0.648 ± 0.006	0.63 ± 0.01	0.71 ± 0.01	3
H ₂ O-2	0.850 ± 0.009	0.841 ± 0.006	0.84 ± 0.02	0.94 ± 0.02	3
FeH _z	1.12 ± 0.07	1.34 ± 0.07	1.2 ± 0.2	1.2 ± 0.1	4
FeH _J	1.16 ± 0.02	1.22 ± 0.02	1.23 ± 0.07	1.22 ± 0.04	4
VO _z	1.18 ± 0.01	1.13 ± 0.02	1.17 ± 0.03	1.10 ± 0.02	4
KI _J	1.158 ± 0.006	1.157 ± 0.008	1.19 ± 0.02	1.12 ± 0.01	4
H-cont	0.931 ± 0.005	0.910 ± 0.005	0.92 ± 0.02	0.90 ± 0.01	4
H ₂ O-J	0.882 ± 0.005	0.999 ± 0.006	0.66 ± 0.01	0.93 ± 0.02	5
H ₂ O-H	0.851 ± 0.004	0.812 ± 0.004	0.79 ± 0.01	0.88 ± 0.01	5
H ₂ O-K	1.008 ± 0.006	1.036 ± 0.005	0.98 ± 0.01	1.14 ± 0.01	5
CH ₄ -J	0.853 ± 0.004	0.875 ± 0.005	0.99 ± 0.01	0.91 ± 0.01	5
CH ₄ -H	1.048 ± 0.004	1.142 ± 0.004	1.05 ± 0.01	1.020 ± 0.009	5
CH ₄ -K	1.018 ± 0.005	1.036 ± 0.003	1.042 ± 0.009	1.046 ± 0.009	5
K/J	0.456 ± 0.002	0.492 ± 0.002	0.380 ± 0.004	0.356 ± 0.004	5
H-dip	0.484 ± 0.002	0.502 ± 0.002	0.486 ± 0.006	0.487 ± 0.004	6
Line	HD 164507 B	V478 Lyr C	CD-28 8692 B	LT UMa B	Reference
	(Å)	(Å)	(Å)	(Å)	
Na I 1.138 μm	10.3 ± 0.3	9.6 ± 0.3	8.6 ± 0.7	7.7 ± 0.6	4
K I 1.169 μm	6.0 ± 0.3	5.5 ± 0.3	8.0 ± 0.7	2.8 ± 0.5	4
K I 1.177 μm	6.9 ± 0.2	8.2 ± 0.3	11.0 ± 0.6	3.9 ± 0.4	4
K I 1.244 μm	5.3 ± 0.2	5.0 ± 0.3	6.9 ± 0.7	5.4 ± 0.5	4
K I 1.253 μm	5.0 ± 0.2	4.9 ± 0.2	6.7 ± 0.6	4.4 ± 0.5	4

Notes: References: 1: Allers et al. (2007); 2: McLean et al. (2003); 3: Slesnick, Hillenbrand & Carpenter (2004); 4: Allers & Liu (2013); 5: Burgasser et al. (2006); and 6: Burgasser et al. (2010).

Table 5. Summary of the inferred properties for HD 164507 B, V478 Lyr C, and CD-28 8692 B.

Name	Spectral type	T_{eff} (K)	Age (Gyr)	[Fe/H] (dex)
HD 164507 B	L1	2100 ± 30	3.0–5.9	0.03–0.19
V478 Lyr C	L1:	1740 ± 60	0.1–0.37	...
CD-28 8692 B	L2	1960 ± 30	4.5	−0.22

Notes: T_{eff} for HD 164507 B and CD-28 8692 B are computed using the spectral type to T_{eff} polynomial relations for field-age objects derived in Filippazzo et al. (2015), while for V478 Lyr C we used the M_H to T_{eff} polynomial relation for young objects presented in the same paper.

**Figure 7.** Same as Fig. 5, but for LT UMa B.

Flower (1996) to obtain $T_{\text{eff}} = 5290$ K. More recently Stevens, Stassun & Gaudi (2017) combined optical and near-IR photometry,

and derived $T_{\text{eff}} = 5324 \pm 26$ K. They combined this photometric temperature with the parallax from *Gaia* DR1 (Gaia Collaboration et al. 2016b; Lindegren et al. 2016) and estimated the angular diameter, finding $\theta = 174.5 \pm 1.9$ μas. Stassun et al. (2018) combined literature photometry, *Gaia* DR2 astrometry, and various colour- T_{eff} , T_{eff} -radius, and T_{eff} -mass empirical relations to determine the basic properties of LT UMa. They found $T_{\text{eff}} = 5351$ K, $\log g = 4.51 \pm 0.28$, $R_* = 0.88 \pm 0.11 R_{\odot}$, and $M_* = 0.92 \pm 0.12 M_{\odot}$. *Gaia* DR2 quotes $T_{\text{eff}} = 5342^{+92}_{-58}$ K, and the best-fitting template used for RV measurement has $T_{\text{eff}} = 5250$ K, $\log g = 4.5$, and $[\text{Fe}/\text{H}] = 0.0$, all in good agreement with the literature values. Finally, we determined T_{eff} through SED fitting, using the Virtual Observatory SED Analyzer⁹ (VOSA; Bayo et al. 2008). Given its brightness and relative proximity, LT UMa has photometric data covering the full range from far-UV to mid-IR. We fit this SED with the BT-Settl models (Allard et al. 2012b), available through VOSA, and found $T_{\text{eff}} = 5300$ K. Combining our VOSA-based estimate with all the values found in the literature, we adopted $T_{\text{eff}} = 5300 \pm 50$ K. VOSA measures $\log_{10}(L_{\text{bol}}/L_{\odot}) = -0.3091^{+0.0049}_{-0.0050}$ implying a radius $R_* = 0.837 \pm 0.016 R_{\odot}$.

The primary was found to be active by Strassmeier et al. (2000), who measured the strength of the Ca II H and K lines. Pace (2013) used the Strassmeier et al. (2000) measurements and derived an equivalent of the S-index in the Mount Wilson scale, and then used the procedure of Noyes et al. (1984) to convert the S-index into R'_{HK} , and measured $\log R'_{\text{HK}} = -4.443$. We used this value together with the calibrations of Mamajek & Hillenbrand (2008) to estimate the age of this system. Equation (3) from Mamajek & Hillenbrand (2008), based on chromospheric activity, leads to an

⁹<http://svo2.cab.inta-csic.es/theory/vosa/index.php>

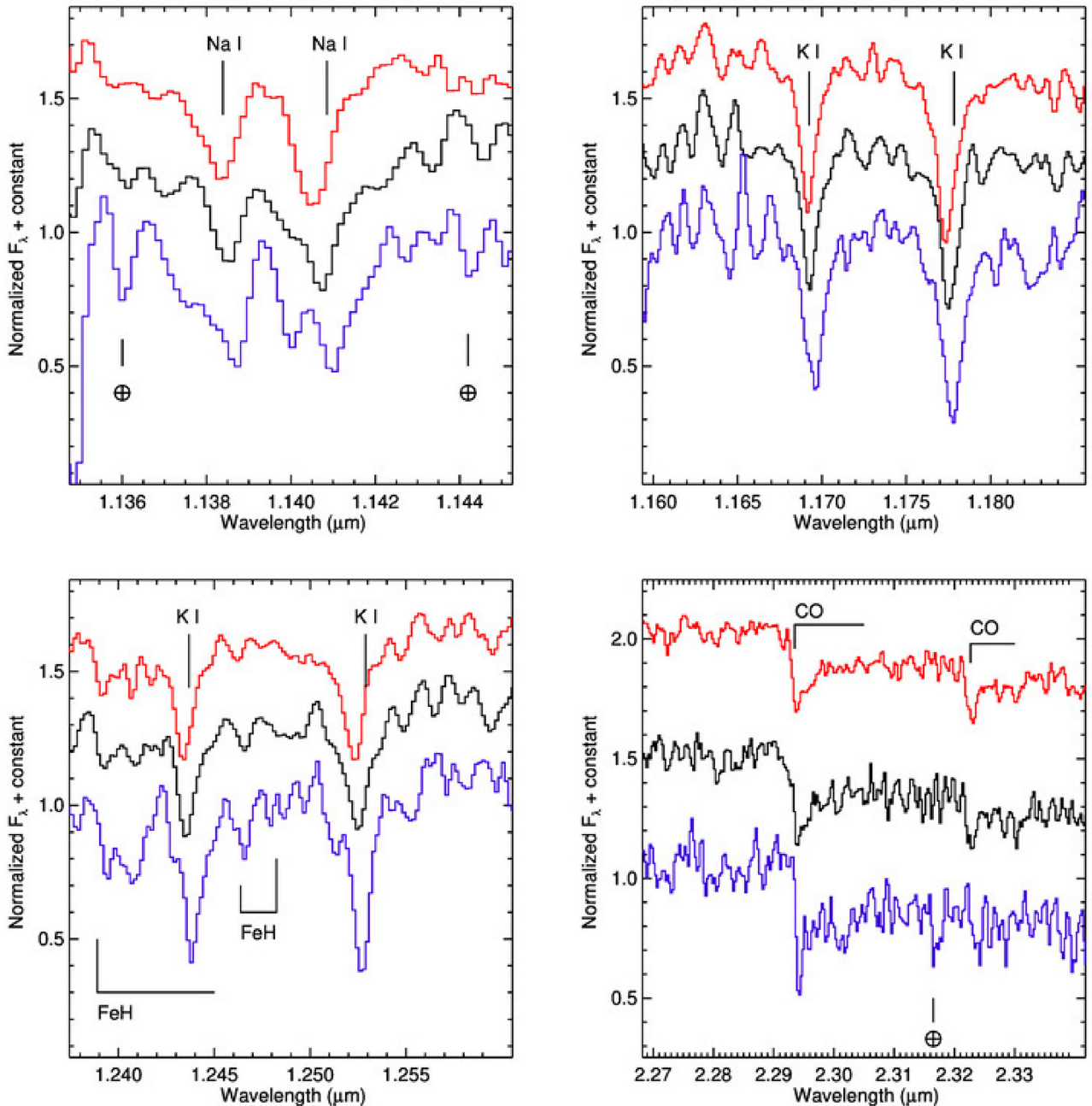


Figure 8. A direct comparison of the main absorption features in the spectra of V478 Lyr C (red), HD 164507 B (black), and CD-28 8692 B (blue). Features likely due to telluric absorption are labelled with the symbol \oplus . All spectra are smoothed down to a resolution of 3 \AA pixel^{-1} to reduce the noise. The alkali lines in V478 Lyr C and HD 164507 B show remarkable similarity, while those in CD-28 8692 B are deeper and broader, confirming the known trend with metallicity (see e.g. Kirkpatrick et al. 2010). The CO band head at 2.293 \mu m appears deeper in CD-28 8692 B as well, while the CO band head at 2.322 \mu m is in a region of too low signal-to-noise-ratio.

age of 0.41 Gyr. We also used the activity to Rossby number correlation from Mamajek & Hillenbrand (2008, their equation 7) and their recalibrated colour-dependent version of the Skumanich law (Skumanich 1972), to derive a gyrochronology age of 0.70 Gyr.

The TripleSpec spectrum of the companion is presented in Fig. 3, and we classify it as M9 V via template fitting. The spectrum does not show signs of youth (i.e. low surface gravity), and the gravity-sensitive spectral indices give a classification of FLD-G. As discussed in Section 4.2, low-gravity features tend to disappear by

the time the object reaches ~ 400 Myr. The absence of low-gravity features from the spectrum of LT UMa B is therefore consistent with the age of the system (0.41–0.70 Gyr) and its solar metallicity. Using the Filippazzo et al. (2015) relation we obtain $T_{\text{eff}} = 2395 \pm 29 \text{ K}$, which implies a mass in the $48 - 77 M_{\text{Jup}}$ range. We determined L_{bol} for the M dwarf following the same procedure described in Section 4.1. The best-fitting model has $T_{\text{eff}} = 2300 \text{ K}$, $\log g = 5.0$, and $[\text{Fe}/\text{H}] = +0.5 \text{ dex}$. The radius is $1.13 R_{\text{Jup}}$, in good agreement with the model-predicted radius ($1.18 R_{\text{Jup}}$). The bolometric lumi-

osity is $\log_{10}(L_{\text{bol}}/L_{\odot}) = -2.968_{-0.029}^{+0.028}$. The best-fitting model can be seen in Fig. 7. The quality of the fit is poor. The model has a triangular-shaped *H* band that is not present in the target, which instead displays a flat *H*-band spectrum. The alkali lines in the *J* band are also weaker in the model compared to the observed ones.

5 COMPARISON OF L DWARF SPECTRAL FEATURES

Despite the relatively small sample size, it is none the less interesting to compare the spectroscopic features in our newly discovered L companions. In particular, V478 Lyr C, HD 164507 B, and CD-28 8692 B offer an interesting comparison set. With very similar spectral type (L1:, L1, and L2, respectively), but different ages and metallicity, these three objects can be used to qualitatively determine the dependence of spectral features on these parameters. Properties for these three UCDs relevant to this analysis are summarized in Table 4 and 5. Fig. 8 shows the normalized IR spectra, centred around four of the main absorption features in the spectra of early L dwarfs: the Na I doublet at $\sim 1.139 \mu\text{m}$, the K I doublets at $\sim 1.173 \mu\text{m}$ and $\sim 1.248 \mu\text{m}$, and the CO band head at $2.30 \mu\text{m}$.

The alkali lines in V478 Lyr C and HD 164507 B show remarkable similarity, while those in CD-28 8692 B are deeper and broader. FeH absorption in the $1.24\text{--}1.25 \mu\text{m}$ range is also stronger in CD-28 8692 B, as expected from its age, which confirms the known trend of alkali lines and hydride bands with metallicity (see e.g. Kirkpatrick et al. 2010). Surprisingly, the CO band at $2.293 \mu\text{m}$ appears deeper in CD-28 8692 B as well, while the band at $2.322 \mu\text{m}$ is in a region of too low signal-to-noise ratio. While the strength of this CO band is relatively insensitive to changes in effective temperature in the L0–4 range (Cruz et al. 2018), blue L dwarfs and L subdwarfs have weaker CO bands than their solar-metallicity counterparts (see e.g. Zhang et al. 2017). A strong CO band has been previously observed in the blue L1 dwarf 2MASS J17561080+2815238 (Kirkpatrick et al. 2010).

Comparison of the spectral indices and equivalent widths presented in Table 4 as a function of the age and metallicity for these three systems leads to some preliminary considerations:

(i) the ‘water-based’ indices H_2O , $\text{H}_2\text{O}-J$, $\text{H}_2\text{O}-H$ and, to a lesser extent, H_2OD and $\text{H}_2\text{O}-K$ appear sensitive to metallicity – e.g. $\text{H}_2\text{O}-J = 0.659 \pm 0.013$ at $\text{Fe}/\text{H} = -0.22$ dex versus $\text{H}_2\text{O}-J = 0.8819 \pm 0.0054$ at $\text{Fe}/\text{H} = 0.03\text{--}0.19$ dex;

(ii) the H_2OD and $\text{H}_2\text{O}-J$ indices seem sensitive to age (i.e. surface gravity) too;

(iii) the K I lines are sensitive to age (i.e. surface gravity) but also metallicity, becoming stronger (i.e. having larger equivalent width) as age increases, but weaker at higher metallicity. As a result, the young ($\approx 100\text{--}370$ Myr) L1: V478 Lyr C has K I lines of roughly equal strength as the older (3.0–5.9 Gyr) but metal-rich L1 HD 164507 B (5.52, 8.20, 5.05, and 4.89 \AA for V478 Lyr C versus 5.97, 6.87, 5.28, and 5.03 \AA for HD 164507 B).

Followup of a larger sample of benchmark L dwarfs is fundamental to better identify/quantify possible dependencies of the above spectral features on age and metallicity.

6 CONCLUSIONS

We have presented seven multiple systems discovered in *Gaia* DR2 data, identified as part of our GUCDS project. The systems pre-

sented here include an L1 companion to the G5 IV star HD 164507, an L1: companion to the RS CVn star V478 Lyr, three low-mass binaries consisting of late Ms and early Ls, an L2 companion to the metal-poor K5 V star CD-28 8692, and an M9 V companion to the young variable K0 V star LT UMa. The HD 164507 and CD-28 8692 systems are particularly important benchmarks, because the primaries are very well characterized and offer excellent constraints on the atmospheric parameters of the companion. While the HD 164507 AB system is slightly metal rich, the CD-28 8692 AB system is slightly metal poor, and therefore cover an exotic region of the parameter space, where observational constraints on theoretical models is currently scarce. The V478 Lyr ABC system is a nice addition to the sample of wide low-mass tertiary components to tight binaries, a population of crucial importance to validate formation theories for tight binaries.

We have also reported the discovery of the currently widest L+L binary known – the 2MASS J01390902+8110003 + 2MASS J01385969+8110084 system, with a projected separation of about 960 au. This system, together with the other two wide low-mass wide binaries presented here, pose an increasing challenge to models of formation and evolution of wide low-mass binaries.

A first, qualitative analysis of the sample reveals tentative correlations between spectral indices, equivalent widths, and age and metallicity for the UCDs presented here. Analysis of a larger sample of benchmarks will provide stronger constraints on such correlations, and *Gaia* DR2 will play a cornerstone role in shaping our understanding of ultracool atmospheres.

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APPENDIX A: OBSERVING LOG

Table A1. Log for the Palomar TripleSpec observations.

Name	Night (UT)	Exp. time DIT (s) × NDIT	Standard	Standard V mag	Standard exp. time DIT (s) × NDIT
HD 164507 B	2018-04-28	240 × 8	HD165029	6.42	10 × 4
V478 Lyr C	2018-04-29	300 × 8	HD192538	6.46	10 × 4
CD-28 8692 B	2018-04-28	240 × 8	HD98949	7.52	10 × 4
2MASS J18392740+4424510	2018-04-29	300 × 8	HD192538	6.46	10 × 4
2MASS J01390902+8110003	2018-10-16	180 × 4	HD8424	6.36	5 × 4
2MASS J01385969+8110084	2018-10-16	240 × 8	HD8424	6.36	5 × 4
2MASS J23253550+4608163	2018-10-16	120 × 4	HD219290	6.31	5 × 4
2MASS J23253519+4608098	2018-10-16	300 × 8	HD219290	6.31	5 × 4
LT UMa B	2019-04-16	300 × 8	HD91311	6.53	30 × 4

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