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Primeval very low-mass stars and brown dwarfs – VII. The discovery of the first wide M + L extreme subdwarf binary

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ABSTRACT

I present the discovery of the first wide M + L extreme subdwarf binary system Gaia J0452–36AB. The binary is located at a distance of $137.27^{+0.68}_{-0.67}$ pc with a projected separation of 15828 ± 78 au. I classified Gaia J0452–36AB as esdM1 and esdL0 subdwarfs, respectively. Gaia J0452–36AB have typical halo kinematics, metallicity of $[\text{Fe}/\text{H}] \approx -1.4$, and temperature of ~ 3550 and 2600 K, respectively. Gaia J0452–36AB is a pair of very low-mass stars with masses of $0.151^{+0.029}_{-0.019}$ and $0.0855^{+0.0014}_{-0.0010} M_{\odot}$, and is a gravitationally bound system. I tested the metallicity consistency of existing M subdwarf classification schemes with Gaia J0452–36AB and a sample of M and L subdwarfs with known metallicity. I found that the metallicity of each M subclass defined by the the metallicity index $\zeta_{\text{CaH/TiO}}$ is not consistent from mid-to-late M subtypes. Because late-type M and L subdwarfs have dusty atmospheres and high surface gravity which have significant impacts on CaH and TiO indices that used in the classification. The metallicity scale of late-type M subdwarfs would be overestimated by the $\zeta_{\text{CaH/TiO}}$ index. I discussed the mass range of M subdwarfs, and explained the lack of late-type M extreme and ultra subdwarfs, and decreasing binary fraction from sdM, to esdM, and usdM subclasses. The four M subclasses have different mass ranges. The comparison between M subclasses is between populations in different mass ranges. I also present the discovery of Ruiz 440-469B, an M8 dwarf wide companion to a cool DA white dwarf, Ruiz 440-469.

Key words: binaries: general – brown dwarfs – stars: individual: Gaia J045238.82–361001.3, Gaia J045245.87–360843.8, Gaia J115626.32–322227.1 – stars: low-mass – stars: Population II – subdwarfs.

1 INTRODUCTION

Field red dwarfs have temperature of ~ 2000 – 4000 K, and have molecules (TiO, CaH, and H₂O) in their atmospheres. They are very low-mass stars with mass of ~ 0.08 – $0.6 M_{\odot}$. Red subdwarfs have subsolar metallicity and lower opacity than red dwarfs. Consequently, red subdwarfs have bluer colours than red dwarfs and appear below the main sequence on the Hertzsprung–Russell diagram (HRD; Hertzsprung 1909; Russell 1914). Red subdwarfs have higher temperature (T_{eff}) than red dwarfs of the equivalent mass (fig. 9 in Zhang et al. 2017b, hereafter *Primeval II*). Molecular features start to appear in the spectra of red subdwarfs at lower temperature than red dwarfs (e.g. fig. 9; Jao et al. 2008). Red subdwarfs have smaller radii than red dwarfs of the equivalent T_{eff} (Kesseli et al. 2019). Red subdwarfs also have lower and narrower mass range than red dwarfs.

In general, red dwarfs are orbiting in the Galactic disc, while older red subdwarfs are kinematically associated with the halo or thick disc with relatively higher space velocities. Red subdwarfs have spectral types of late-type K, M, and early-type L. Early-type M subdwarfs have lower T_{eff} than M dwarfs with equivalent subtypes due to much lower masses. Mid- and late-type M, and L subdwarfs have similar or higher mass than dwarfs with equivalent subtypes thus also have higher T_{eff} (fig. 4; Zhang et al. 2018a, hereafter *Primeval III*).

Dwarfs with spectral types of $\geq M7$ have dust formation in their atmospheres (Jones & Tsuji 1997) and thus are referred to as ultracool dwarfs (UCD; e.g. Kirkpatrick, Henry & Irwin 1997). Likewise, subdwarfs with spectral types of late-type M or L are called ultracool subdwarfs (UCSD; e.g. Lépine, Shara & Rich 2003a). UCDS and UCSDs are extremely low-mass stars or brown dwarfs with mass of $\lesssim 0.1 M_{\odot}$.

The Kapteyn’s star is the nearest cool subdwarf (at 3.93 pc; Gaia Collaboration et al. 2018) with a spectral type of sdM1 and a mass of $\sim 0.2 M_{\odot}$ (fig. 9, *Primeval II*). It was first discovered as a high proper motion star (Kapteyn 1897; R. Innes; Gill 1899). Then, it

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was classified as an M subdwarf (Kuiper 1940) after the discovery of the HRD and definition of cool subdwarfs (Kuiper 1939). To date, thousands of M subdwarfs (Zhang et al. 2013; Savcheva, West & Bochanski 2014; Zhong et al. 2015; Jao et al. 2017; Zhang et al. 2019a), hundreds of late-type M subdwarfs (Lépine, Rich & Shara 2003b; Burgasser, Cruz & Kirkpatrick 2007; Lépine & Scholz 2008; Lodieu et al. 2012, 2017; Kirkpatrick et al. 2016), and about 66 L subdwarfs (Burgasser et al. 2003; Kirkpatrick et al. 2014; hereafter *Primeval I*, Zhang et al. 2017a, *Primeval III*; hereafter *Primeval IV*, Zhang et al. 2018b) have been discovered with modern sky surveys. About 41 T subdwarfs have also been discovered (e.g. Burgasser et al. 2002; Pinfield et al. 2012; Mace et al. 2013; Burningham et al. 2014) and studied in the literature (hereafter *Primeval VI* Zhang et al. 2019b).

Gizis (1997) classified M dwarfs/subdwarfs into three metallicity subclasses: M dwarfs (M V), M subdwarf (sdM), and extreme subdwarf (esdM) based on their broad-band absorption features (CaH and TiO). The metallicity consistency of these subclasses are tested with observed HRD of globular clusters for early-type M subdwarfs. Then, Lépine, Rich & Shara (2007) defined a metallicity index ($\zeta_{\text{CaH/TiO}}$) with CaH2, CaH3, and TiO5 spectral indices (Reid, Hawley & Gizis 1995), and revised the classification into four subclasses: M dwarfs (dM), sdM, esdM, and ultra subdwarf (usdM). The $\zeta_{\text{CaH/TiO}}$ index was slightly refined a few times (Dhital et al. 2012; Lépine et al. 2013; Zhang et al. 2019a). The metallicity consistency of M subclasses are tested with wide binaries of early- and mid-type M subdwarfs. However, the test was not possible across late-type M subdwarfs due to the lack of wide UCSD binaries.

There are about four binary systems with late-type M or L subdwarf components known in the literature. LSR 1610–0040 (Lépine et al. 2003b) is an unresolved metal-poor ($[\text{Fe}/\text{H}] \approx -1.0$) binary (Koren et al. 2016) that is composed of a late-type M subdwarf and a degenerate brown dwarf (D-BD; *Primeval VI*). HD 114762AB is a close sdF9 + sdM9 binary with $[\text{Fe}/\text{H}] \approx -0.7$ (Bowler, Liu & Cushing 2009). SDSS J1416+13AB is a wide sdL7 + sdT7.5 subdwarf binary with $[\text{Fe}/\text{H}] \approx -0.3$ (Burningham et al. 2010). GJ 660.1AB is a wide sdM1 + sdM7 binary with $[\text{Fe}/\text{H}] \approx -0.63$ (Aganze et al. 2016).

Wide F/G/K/M + L subdwarf binaries with well-constrained properties are ideal benchmarks to: (1) test metallicity consistency in the classification of M subdwarfs (e.g. Lépine et al. 2007); (2) calibrate precise metallicity measurements of M and L subdwarfs in the near-infrared (NIR; e.g. Rojas-Ayala et al. 2012; Newton et al. 2015); and (3) test the performance of ultracool atmospheric models and very low-mass evolutionary models in the subsolar metallicity domain (Allard & Hauschildt 1995; Allard 2014; Chabrier & Baraffe 1997; Baraffe et al. 1997; Burrows et al. 2001; Marley et al. 2019, in prep.). However, such binaries have not been discovered in the literature. Therefore, I conducted a search for wide L subdwarf binaries with the second data release (DR2) of *Gaia* (Gaia Collaboration et al. 2018) and the Visible and Infrared Survey Telescope for Astronomy’s (VISTA) Hemisphere Survey (VHS; McMahon et al. 2013).

This is the seventh paper of a series titled *Primeval very low-mass stars and brown dwarfs*. The first to the fifth papers of the series are focused on L subdwarfs, transitional brown dwarfs (T-BDs), and the substellar transition zone (*Primeval I*, *Primeval II*, *Primeval III*, *Primeval IV*; hereafter *Primeval V* Zhang, Burgasser & Smith 2019c). Population properties of metal-poor D-BDs are discussed in the sixth paper (*Primeval VI*). Some of these results are summarized in Zhang (2018). In this paper, I present the first wide M + L extreme subdwarf binary discovered with the *Gaia* and VHS

surveys. Candidate selection is described in Section 2. Sections 3 and 4 present spectroscopic observations and characterization of two wide binary systems, respectively. Metallicity consistency and mass ranges of M subclasses are discussed in Sections 5 and 6, respectively. Section 7 presents the summary and conclusions.

2 CANDIDATE SELECTION

2.1 L subdwarf candidates

L subdwarfs have subsolar metallicity and are members of the Galactic thick disc or halo. Therefore, they have distinctive photometric colours, proper motion, and tangential velocity from field objects (*Primeval I*). I conducted a search for L subdwarf candidates by a combined use of *Gaia* DR2 astrometric and photometric catalogues and the 2018 release of VHS photometric catalogue. Fig. 21 of *Primeval IV* shows that L subdwarfs are distinctive from field dwarfs on the M_G versus $J - K$ HRD. Fig. 1 shows the modified M_G versus $G - G_{\text{RP}}$ and M_G versus $J - K$ HRD of *Primeval IV*. 20 known L subdwarfs observed in *Gaia* DR2 can be separated from M and L dwarfs by the dashed line in Fig. 1, defined by equations (1) and (2). I also applied two cuts defined by equations (3) and (4) in the $G - J$ versus $J - K$ space to removed main sequence stars due to mismatches between *Gaia* and VHS.

$$M_G > 10.0(J - K) + 7.0 \quad (1)$$

$$M_G > 1.25(J - K) + 13.5625 \quad (2)$$

$$J - K < G - J - 3.0 \quad (3)$$

$$J - K < 0.2(G - J) \quad (4)$$

$$M_G > 10.0(J - K_s) + 7.5 \quad (5)$$

$$M_G > 1.25(J - K_s) + 13.625 \quad (6)$$

$$J - K_s < G - J - 2.95 \quad (7)$$

$$J - K_s < 0.2(G - J) - 0.05 \quad (8)$$

Note that the NIR photometry in equations (1)–(4) is in Mauna Kea Observatories (MKO) system, e.g. the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007). UKIDSS and VISTA have very similar J band photometry but slightly different in K/K_s bands. Fig. 7 of *Primeval VI* shows that MKO K photometry of L0–6 dwarfs can be transformed to VISTA K_s photometry by $K - K_s = -0.05$. The criteria to selection L subdwarfs with *Gaia* and VISTA are described in equations (5)–(8).

$$G - G_{\text{RP}} > 1.3 \quad (9)$$

$$G - J < 6.0 \quad (10)$$

$$13.0 < J < 18.5 \quad (11)$$

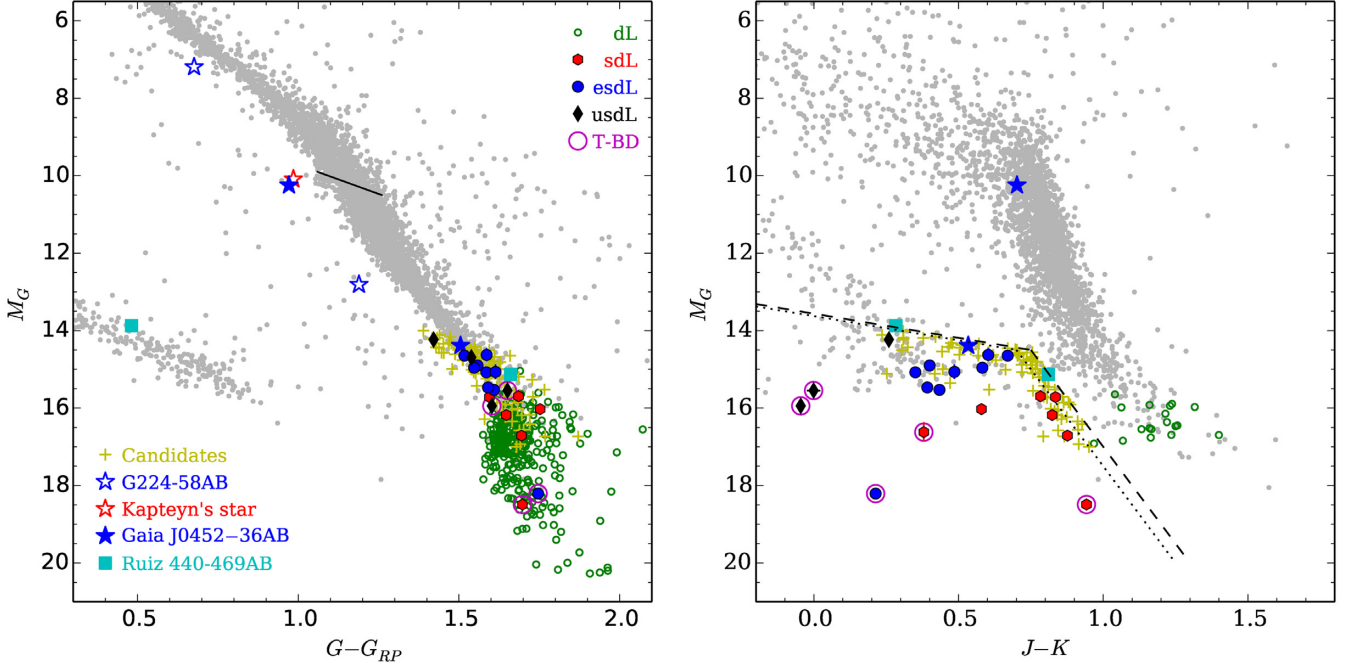


Figure 1. HRDs for Gaia J0452–36AB (blue five-pointed stars), Ruiz 440-469AB (cyan squares), and other L subdwarf candidates (yellow crosses) selected from *Gaia* and VHS in comparison to the Kapteyn’s star (sdM1; red open five-pointed star), G224-58AB (esdK5 + esdM5.5; blue open five-pointed stars; Zhang et al. 2013; Pavlenko et al. 2015), L subdwarfs (fig. 21, *Primeval IV*), and field objects. The $J - K_{SV}$ colour of Gaia J0452–36B, Ruiz 440-469B, and L subdwarf candidates are transformed to $J - K$ colour in the right-hand panel by $K - K_s = -0.05$ (fig. 7, *Primeval VI*). Metal-poor T-BDs are indicated with magenta circles. Grey dots are 5000 objects selected from *Gaia* DR2 and Large Area Survey of UKIDSS with distance < 100 pc, $180^\circ < \text{RA} < 220^\circ$ and $0^\circ < \text{Dec.} < 20^\circ$. The two grey sequences are white dwarfs (left) and main-sequence stars (right). Some bright field stars are scattered in the right-hand panel mostly because they are too bright in the UKIDSS fields. Dashed and dotted lines in the right-hand panel indicate my selection cuts for L subdwarf candidates in UKIDSS ($J - K$) and VISTA ($J - K_s$), respectively. A black line on the left-hand panel [from (1.06, 9.9) to (1.26, 10.5)] indicates a gap among M dwarfs (Jao et al. 2018) associated with mixing of ^3He that reduced the nuclear fusion rate around $0.34\text{--}0.36 M_\odot$ (Baraffe & Chabrier 2018; MacDonald & Gizis 2018).

$$J_{\text{Err}} < 0.1 \quad (12)$$

$$K_s > 12.0 \quad (13)$$

$$K_s \text{Err} < 0.2 \quad (14)$$

$$|b| > 15^\circ \quad (15)$$

$$\text{parallax} > 5.0 \quad (16)$$

$$\text{parallax}/\text{parallax_error} > 5.0 \quad (17)$$

$$V_{\text{tan}} > 100 \text{ km s}^{-1} \quad (18)$$

Equations (9)–(14) show six extra photometric criteria applied in my selection. The region within 15° from the Galactic plane is avoided (equation 15). These 20 known L subdwarfs in *Gaia* DR2 are within 120 pc, thus I only selected objects within 200 pc in *Gaia* DR2 (equations 16 and 17). Fig. 23 of *Primeval IV* shows that L subdwarfs and dwarfs are relatively well separated by their

tangential velocity (V_{tan}) at 100 km s^{-1} . Therefore, I selected objects with $V_{\text{tan}} > 100 \text{ km s}^{-1}$ (equation 18).

I carried out a by-eye image check of objects survived my selection criteria (equation 1–18). 88 objects were left on the list of L subdwarf candidates. Three of them are previous known UCSDs: WISE J001450.17–083823.4 (Kirkpatrick et al. 2014; Luhman & Sheppard 2014); ULAS J033351.10+001405.8 (Lodieu et al. 2012); and SSSPM J10130734–1356204 (Scholz et al. 2004), and were classified as L subdwarfs in *Primeval I*. Note that most of these 20 known L subdwarfs in *Gaia* DR2 are in the northern sky, and the VHS is a southern sky survey. Some L subdwarfs could be missed in the cross-matching between *Gaia* and VHS due to high proper motion and long baseline.

2.2 Binaries of L subdwarf candidates

I cross-matched these 88 L subdwarf candidates with a sample of about 1.8 million *Gaia* DR2 sources within 200 pc and off the Galactic plane ($|b| > 15^\circ$) by proper motion within a separation of 3 arcmin. I allowed a match error of 5 mas yr^{-1} for both μ_{RA} and μ_{Dec} , and found two wide binaries with common proper motions. Components of each pair also have very close parallax distances (see Table 1). I also cross-matched these 20 L subdwarfs observed in *Gaia* DR2 (table 9; *Primeval IV*) with these 1.8 million *Gaia* DR2 sources in the same way, but did not find any binary.

Gaia DR2 4818823636756117504 (Gaia J045238.82–361001.3; hereafter Gaia J0452–36A) and Gaia DR2 4818823808553134592 (Gaia J045245.87–360843.8; hereafter Gaia J0452–36B) are

Table 1. Properties of Gaia J0452–36AB and Ruiz 440-469AB wide binary systems.

Component	Gaia J0452–36A	Gaia J0452–36B	Ruiz 440-469A	Ruiz 440-469B
Gaia DR2	4818823636756117504	4818823808553134592	3466916670990633088	3466916778361936000
α (2015.5)	04 ^h 52 ^m 38 ^s .82	04 ^h 52 ^m 45 ^s .87	11 ^h 56 ^m 22 ^s .77	11 ^h 56 ^m 26 ^s .32
δ (2015.5)	−36° 10′ 01″.3	−36° 08′ 43″.8	−32° 23′ 30″.2	−32° 22′ 27″.1
G	15.933	20.120	19.135	20.398
G_{BP}	16.892	21.080	19.407	21.612
G_{RP}	14.962	18.615	18.654	18.737
J (VHS)	13.687 ± 0.002	16.437 ± 0.008	18.150 ± 0.054	16.071 ± 0.009
K_s (VHS)	12.985 ± 0.003	15.954 ± 0.038	17.866 ± 0.171	15.311 ± 0.017
$W1$ (WISE)	12.865 ± 0.024	15.571 ± 0.037	17.334 ± 0.133	15.072 ± 0.034
$W2$ (WISE)	12.701 ± 0.024	15.234 ± 0.068	17.123 ± 0.404	14.750 ± 0.060
π (mas)	7.285 ± 0.036	7.134 ± 0.506	8.854 ± 0.286	8.851 ± 0.818
Distance (pc)	137.27 ^{+0.68} _{−0.67}	140.17 ^{+10.71} _{−9.29}	112.94 ^{+3.77} _{−3.53}	112.98 ^{+11.50} _{−9.55}
μ_{RA} (mas yr ^{−1})	148.45 ± 0.06	147.52 ± 0.79	−206.72 ± 0.61	−209.43 ± 1.93
μ_{Dec} (mas yr ^{−1})	−168.70 ± 0.07	−168.07 ± 1.00	−41.85 ± 0.29	−44.21 ± 0.99
V_{tan} (km s ^{−1})	146.21 ^{+0.72} _{−0.71}	148.58 ^{+11.35} _{−9.85}	112.91 ^{+3.77} _{−3.53}	114.63 ^{+11.67} _{−9.69}
RV (km s ^{−1})	34 ± 23	—	—	—
U (km s ^{−1})	65 ± 9	—	—	—
V (km s ^{−1})	−129 ± 15	—	—	—
W (km s ^{−1})	42 ± 14	—	—	—
Spectral type	esdM1	esdL0	DA WD	M8
T_{eff} (K)	3550 ± 100	2600 ± 100	—	—
[Fe/H]	−1.4 ± 0.2	−1.4 ± 0.2	—	—
log g	5.0 ± 0.2	5.5 ± 0.2	—	—
Mass (M_{\odot})	0.151 ^{+0.029} _{−0.019}	0.0855 ^{+0.0014} _{−0.0010}	—	—
Separation (arcsec)	115.3		77.5	
Projected separation (au)	15828 ± 78		8794 ⁺²⁹² _{−174}	
Projected separation (r_J)	0.092		—	
− U (J)	1.44 × 10 ³³		—	

at a distance of 137.27^{+0.68}_{−0.67} pc separated by 115.3 arcsec corresponding to a projected separation of 15828 ± 78 au. Gaia DR2 3466916670990633088 (Ruiz 440-469; hereafter Ruiz 440-469A) and Gaia DR2 3466916778361936000 (Gaia J115626.32–322227.1; hereafter Ruiz 440-469B) are at a distance of 112.94^{+3.77}_{−3.53} pc separated by 77.5 arcsec, corresponding to a projected separation of 8794⁺²⁹²_{−174} au. Fig. 2 shows the VISTA J -band images of Gaia J0452–36AB and Ruiz 440-469.

The statistic probability that these two pairs of stars separated by a few arcmins have such very close proper motion and distance by random chance is very tiny and negligible (e.g. Zhang et al. 2010). The probability is much smaller if both stars of such a pair are metal-poor or kinematically associated with the halo or thick disc.

3 SPECTROSCOPY

Optical spectra of Gaia J0452–36AB and Ruiz 440-469B were observed as backup targets with the Auxiliary-port CAMera (ACAM; Benn, Dee & Agócs 2008) on the William Herschel Telescope (WHT) under the programme 95-WHT10/19A (PI: M. C. Gálvez Ortiz). The Kapteyn’s star and WISEA J045921.22+154059.2 (W10459; Kirkpatrick et al. 2016) were included in following discussions in Section 5. Therefore, I present their optical to NIR spectra observed with the X-shooter (Vernet et al. 2011) on the Very Large Telescope (VLT).

3.1 William Herschel Telescope

Gaia J0452–36AB were observed with ACAM on 2019 February 3, under the seeing of 1.3 arcsec, and airmass of 2.35 for Gaia J0452–36A and 2.34 for Gaia J0452–36B (Figs 3 and 4). The ACAM wavelength coverage is 390–930 nm. A V400 grism and 1 arcsec slit were used for the ACAM observation, providing a resolving power of 570 at 750 nm. The integration times for Gaia J0452–36AB are 600 and 1200 s, respectively. The peak signal-to-noise ratio (S/N) of their spectra is 74 at 750 nm for Gaia J0452–36A and 21 at 810 nm for Gaia J0452–36B. Ruiz 440-469B was observed on 2019 February 3, under the seeing of 1.3 arcsec, airmass of 2.08, with integration times of 1200 s (Fig. 5). The peak S/N of its spectrum is about 21 at 810 nm. I also observed a known L0 ultra subdwarf (usdL0), SSSPM J10130734–1356204 (SSSPM 1013–13; Scholz et al. 2004, Primeval I). ACAM observational characteristics are summarized in Table 2.

These ACAM spectra were reduced with a standard IRAF package.¹ The flux calibration was achieved with an F8V standard star HD84937 observed in a 1.0 arcsec slit, seeing of 1.0, and airmass of 1.04 on 2019 February 20. Telluric absorptions in ACAM spectra are not corrected.

¹IRAF is distributed by the National Optical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

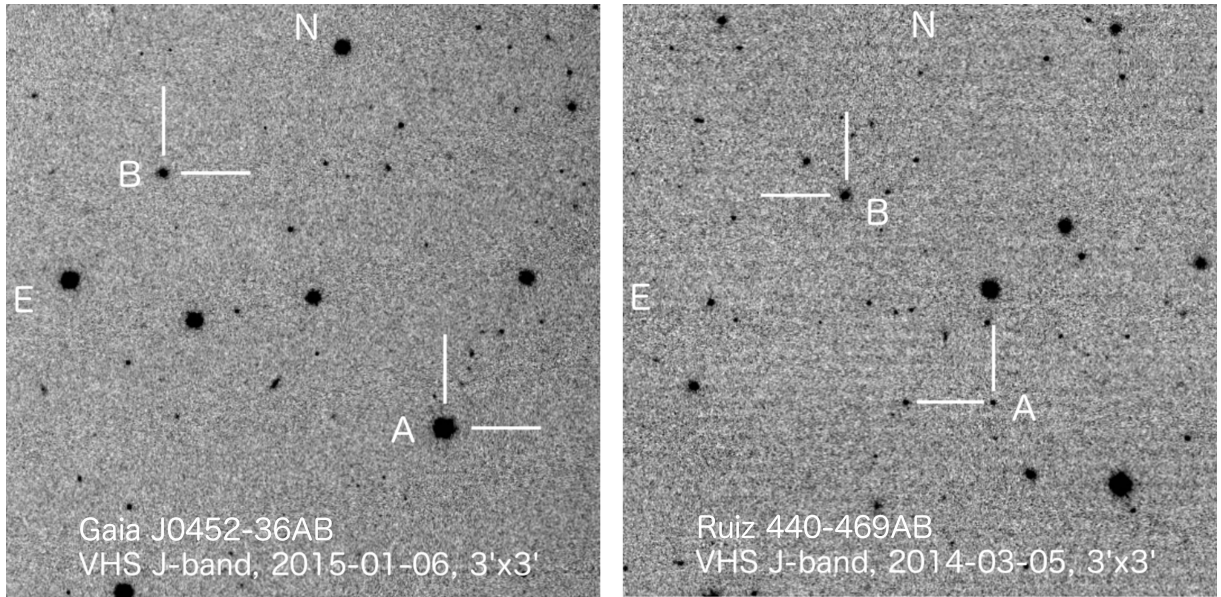


Figure 2. VHS J -band images of fields around Gaia J0452–36AB and Ruiz 440-469AB, which are indicated with white bars (20 arcsec in length). Both fields are 3 arcmin on a side with north up and east to the left. Gaia J0452 – 36AB are moving toward southeast ($138^\circ 65'$) with a proper motion of $224.7 \text{ mas yr}^{-1}$. Ruiz 440-469AB are moving toward southwest ($258^\circ 56'$) with a proper motion of $210.9 \text{ mas yr}^{-1}$.

3.2 Very Large Telescope

The X-shooter spectrum of the Kapteyn’s star (sdM1) was observed in a 1.2 arcsec slit under the seeing of 1.18 arcsec and airmass of 1.31 on 2016 September 14. The total exposure was brake up into two single integrations of 5 s with a AB nod separated by 5 arcsec on the detector. The spectrum was reduced to a flux-calibrated 2D spectrum with the ESO (European Southern Observatory) Reflex (Freudling et al. 2013), then extracted to a 1D spectrum with the IRAF APSUM task. The spectrum displayed in Fig. 6 is smoothed by 51 pixels, which increased the S/N by ~ 7 times. Telluric correction was achieved using a A0 V telluric standard (HD 216009) which was observed just before the target at the airmass of 1.41.

The X-shooter spectrum of WI0459 was observed in a 1.2 arcsec slit under the seeing of 1.23 arcsec and airmass of 1.33 on 2016 January 23. The total exposure was brake up into four single integrations of 290 s for the visible (VIS) arm and 300 s for the NIR arm in an ABBA nodding mode. The reduction procedure is the same as for the Kapteyn’s star. The spectrum of WI0459 has an S/N of 63 at 825 nm, and 40 at 122 and 135 nm. The spectrum displayed in Fig. 7 is smoothed by 101 pixels in the VIS and 51 pixels in the NIR, which increased the S/N by 10 and 7 times, respectively. Telluric correction was achieved using a A1 II telluric standard (HD 40335) which was observed right after the target at the airmass of 1.18.

4 CHARACTERIZATION

4.1 Gaia J0452–36AB

Gaia J0452–36A is located off the dwarf main sequence on the $G - G_{\text{RP}}$ versus M_G HRD (Fig. 1). It has slightly fainter M_G and bluer $G - G_{\text{RP}}$ colour than the Kapteyn’s star and located between two components of the esdK5 + esdM5.5 wide binary G224-58AB (Zhang et al. 2013; Pavlenko et al. 2015). Gaia J0452–36A is below a gap among M dwarfs (Jao et al. 2018) associated with

mixing of ^3He that reduced the nuclear fusion rate in a narrow mass range, around $0.34\text{--}0.36 M_\odot$ for solar metallicity (Baraffe & Chabrier 2018; MacDonald & Gizis 2018). Gaia J0452–36B is not separated from the main sequence in the M_G versus $G - G_{\text{RP}}$ HRD. Because UCSDs have both bluer $G - G_{\text{RP}}$ and brighter M_G than UCDS with equivalent mass, thus located to the upper left of UCDS and associated with higher mass red dwarfs or UCDS on the main sequence (Primeval IV). Fig. 1 (right-hand panel) shows that Gaia J0452–36B has distinctive $J - K$ colour from dwarfs. Early-type M subdwarfs have similar $J - K$ colour as dwarfs (e.g. fig. 1, Primeval I), thus Gaia J0452 – 36A appears like associated with dwarfs on the the main sequence in the M_G versus $J - K$ HRD.

4.1.1 Spectral classification

Fig. 3 shows that the optical spectrum of Gaia J0452–36A fits well to a esdM1 subdwarf, SDSS J120854.81+284031.0 (SD1208, telluric corrected), except the telluric regions. The $\zeta_{\text{CaH/TiO}}$ index of Gaia J0452–36A is 0.306 which is in the range of esdM subclass in the classification scheme of Lépine et al. (2007). Therefore, I classified Gaia J0452–36A as an esdM1 subdwarf. Note that the wavelength ranges used to define the $\zeta_{\text{CaH/TiO}}$ index are outside of telluric regions (table 1 of Lépine et al. 2007). Gaia J0452–36A also shown a weaker TiO absorption around 705–718 nm than the Kapteyn’s star which is an sdM1 subdwarf. The Kapteyn’s star has a metallicity of $[\text{Fe}/\text{H}] \approx -0.99 \pm 0.04$ (Woolf & Wallerstein 2005) and is relatively metal-poor in the sdM subclass (e.g. table 8; Primeval I). Note that the TiO absorption at 718–726 nm in Gaia J0452–36A is contaminated by telluric absorption.

Gaia J0452–36A has a radial velocity (RV) of $34 \pm 23 \text{ km s}^{-1}$. To measure the RV of Gaia J0452–36A, I used SD1208, which has an RV of $-91.08 \pm 3.23 \text{ km s}^{-1}$, as a reference. Strong common absorption lines (e.g. Na D, and Ca II) in Gaia J0452–36A and SD1208 were used to measure their RV difference. Then the

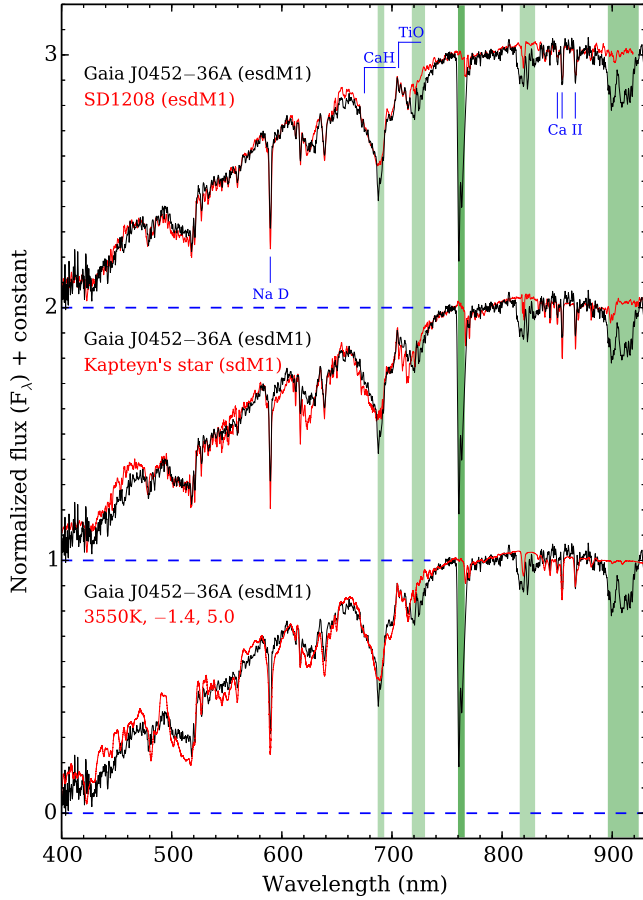


Figure 3. ACAM spectrum of Gaia J0452-36A (without telluric correction) compared to SDSS spectrum of SD1208 (esdM1, telluric corrected), X-shooter spectrum of Kapteyn's star (sdM1, telluric corrected), and a BT-Settl model spectrum with $T_{\text{eff}} = 3600$ K, $[\text{Fe}/\text{H}] = -1.4$, and $\log g = 5.0$. The SDSS spectrum of SD1208 is smoothed by 5 pixels. The X-shooter spectrum of the Kapteyn's star is smoothed by 51 pixels. Telluric absorptions are indicated with shaded green bands. Lighter and thicker shaded bands indicate regions with weaker and stronger telluric effects.

barycentric velocity was corrected for Gaia J0452-36A. I also calculated the space velocity of Gaia J0452-36A based on its astrometry from *Gaia* DR2 and RV measured from its ACAM spectrum. The space velocity of Gaia J0452-36A ($U = 65 \pm 9$ km s $^{-1}$; $V = -129 \pm 15$ km s $^{-1}$; and $W = 42 \pm 14$ km s $^{-1}$) is typical for halo population. The halo membership of Gaia J0452-36AB is robust considering its metallicity ($[\text{Fe}/\text{H}] = -1.4$; see Section 4.1.2) is also typical for halo population.

Primeval I presented a classification scheme for L subdwarfs, and classified L subdwarfs into three subclasses: L subdwarf (sdL), L extreme subdwarf (esdL), and L ultra subdwarf (usdL). Metallicity of each L subclass consistent across subtypes and consistent with that of M0-3 subdwarf subclasses defined by Lépine et al. (2007). Fig. 4 shows the optical spectrum of Gaia J0452-36B compared to known L subdwarfs. Spectral types of these known L subdwarfs are based on the classification scheme of **Primeval I**. The spectrum of Gaia J0452-36B fits well to that of the esdL0 type ULAS J111429.54+072809.5 (UL1114+07) and esdL0.5 type ULAS J135216.31+312327.0 (UL1352+31; **Primeval IV**), particularly at CaH, TiO, VO, CrH, and FeH absorption bands at 670-740 and 790-880 nm, which are sensitive to temperature and metallicity.

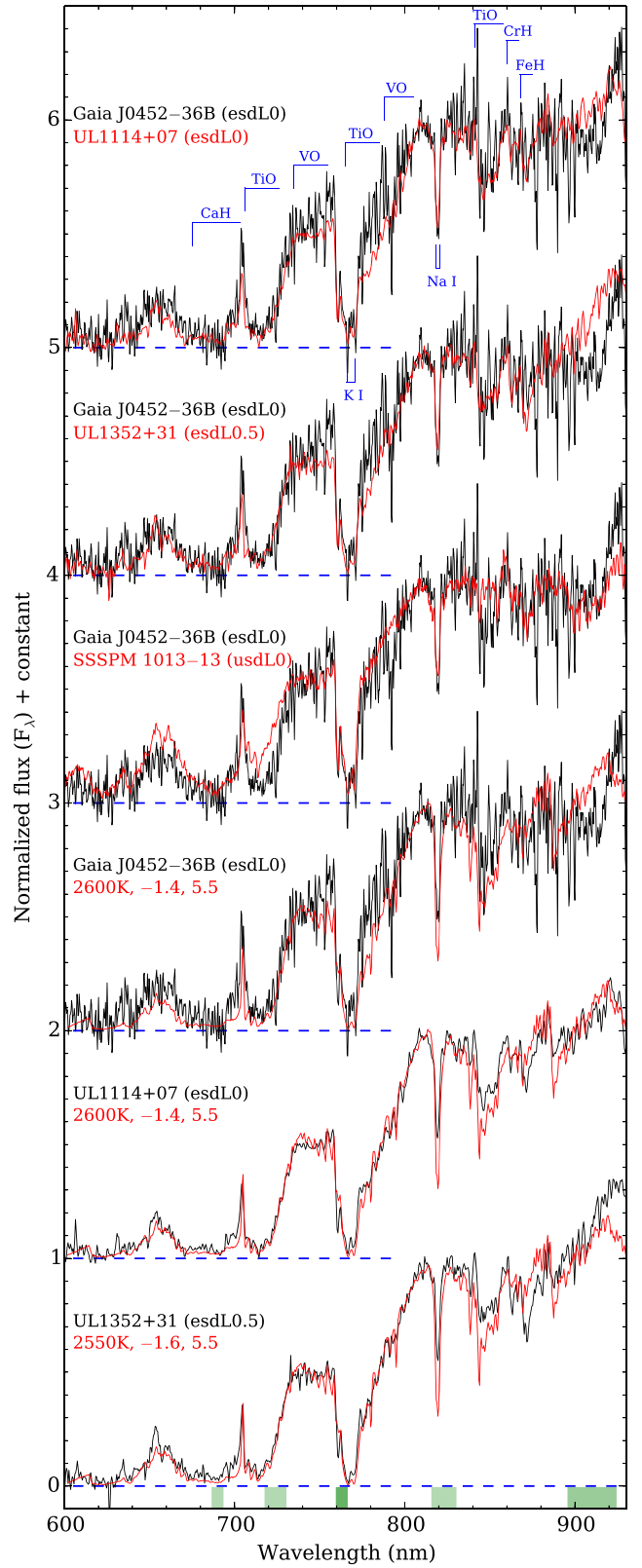


Figure 4. The ACAM spectrum of Gaia J0452-36B compared to UL1114 + 07 esdL0; **Primeval IV**, UL1352+31 esdL0.5; **Primeval IV**, SSSPM 1013-13 (usdL0), and a BT-Settl model spectrum. Telluric absorptions are not corrected (shaded green bands).

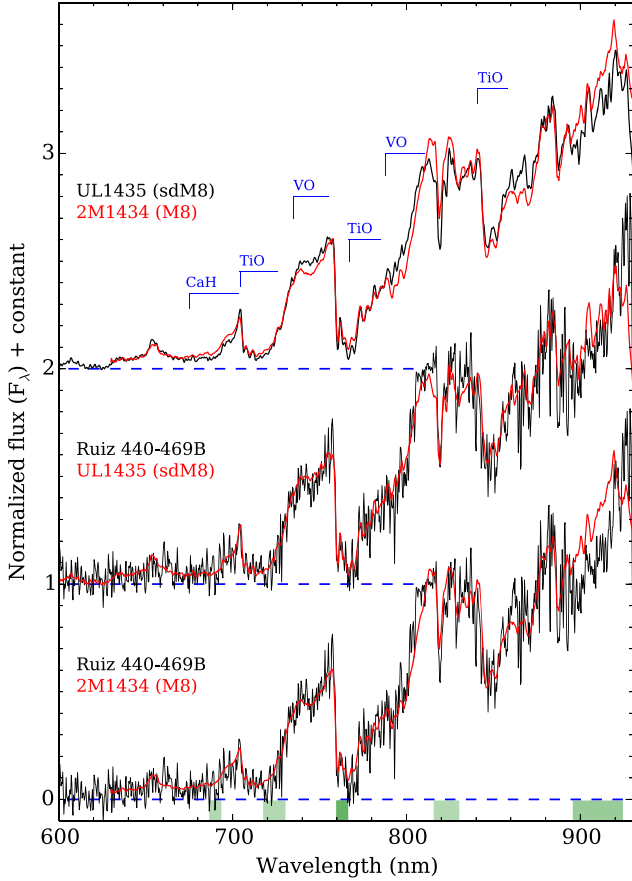


Figure 5. The optical spectrum of Ruiz 440-469B compared to those of UL1435 (sdM8; *Primeval IV*) and 2M1434 (M8; Kirkpatrick et al. 1999). Telluric absorptions are not corrected (shaded green bands).

The flux of Gaia J0452–36B at around 750 and 770–790 nm looks higher than UL1114+07 and UL1352+31. This is not a real feature but caused by contamination of noise. Gaia J0452–36B clearly has slightly stronger TiO absorption at around 720 and 850 nm (sensitive to metallicity) than the usdL0 type SSSPM 1013–13. As a result, I classified Gaia J0452–36B as an esdL0 subdwarf. Note that the TiO absorption around 720 nm in Gaia J0452–36B is partially in a telluric region. However, the telluric absorption is much weaker than the TiO absorption around 720 nm, and has relatively small impact on the TiO absorption band around 720 nm.

4.1.2 Physical properties

I fitted the optical spectra of Gaia J0452–36AB with BT-Settl model spectra (Allard 2014). Figs 3 and 4 show the best-fitting model spectra of Gaia J0452–36AB, which both have $[\text{Fe}/\text{H}] = -1.4$. Gaia J0452–36A has $T_{\text{eff}} = 3550\text{ K}$ and $\log g = 5.0$. Gaia J0452–36B has $T_{\text{eff}} = 2600\text{ K}$ and $\log g = 5.5$. The fitting procedure is described in previous papers of this series. I estimated masses of Gaia J0452–36AB based on the 10 Gyr iso-mass contours predicted by evolutionary models (Baraffe et al. 1997; Chabrier & Baraffe 1997) plotted in the T_{eff} versus $[\text{Fe}/\text{H}]$ space (*Primeval II*, *Primeval III*). Gaia J0452–36AB have masses of $0.151^{+0.029}_{-0.019}$ and $0.0855^{+0.0014}_{-0.0010} M_{\odot}$, respectively.

The Kapteyn’s star has $T_{\text{eff}} = 3570 \pm 160\text{ K}$ and $[\text{Fe}/\text{H}] = 0.99 \pm 0.04$ according to Woolf & Wallerstein (2005). Fig. 6

shows that the X-shooter spectrum of the Kapteyn’s star fitted well to a BT-Settl model spectrum with $[\text{Fe}/\text{H}] = -1.0$, $T_{\text{eff}} = 3600\text{ K}$, and $\log g = 5.0$. Gaia J0452–36A has a weaker TiO absorption band around 710 nm than Kapteyn’s star (Fig. 3), thus certainly have lower metallicity than Kapteyn’s star. With $T_{\text{eff}} = 3600\text{ K}$ and $[\text{Fe}/\text{H}] = -1.0$, Kapteyn’s star would have a mass of $0.21^{+0.06}_{-0.04} M_{\odot}$ (fig. 9, *Primeval II*), which is significant lower than estimates in the literature ($0.274 M_{\odot}$, Kotoneva et al. 2005; $0.281 M_{\odot}$, Anglada-Escude et al. 2014).

Two known M subdwarfs, WI0459 (Kirkpatrick et al. 2016) and SDSS J084648.88+302801.7 (SD0846+30; Zhang et al. 2013), are selected for the discussion in Section 5. I observed an optical to NIR spectrum of WI0459 with the X-shooter (Fig. 7). The optical spectrum of SD0846+30 (Fig. 8) is from the Sloan Digital Sky Survey (SDSS; York et al. 2000). The best-fitting BT-Settl model spectra have $[\text{Fe}/\text{H}] = -1.5$, $T_{\text{eff}} = 3050\text{ K}$, and $\log g = 5.0$ for the esdM6 type WI0459, and $[\text{Fe}/\text{H}] = -2.0$, $T_{\text{eff}} = 3200\text{ K}$, and $\log g = 5.25$ for the usdM6 type SD0846 + 30.

4.1.3 Binary properties

Gaia J0452–36AB are located at a distance of $137.27^{+0.68}_{-0.67}\text{ pc}$ with an angular separation of 115.3 arcsec , that corresponds to a projected separation of $15828 \pm 78\text{ au}$. The projected separation of the system is about 0.092 Jacobi radius (r_J ; tidal radius). This suggests that Gaia J0452–36AB is a gravitationally bound system as its separation is far smaller than the Jacobi radius at an age of around 10 Gyr (Jiang & Tremaine 2010). The binding energy ($-U$) of the system is about $1.44 \times 10^{33} J$.

4.2 Ruiz 440-469AB

Ruiz 440-469A is a cool DA white dwarf (Ruiz 1996) and associated with the white dwarf sequence on both HRD in Fig. 1. Ruiz 440-469B has slightly bluer $J - K$ colour than dwarfs on the main sequence.

Fig. 5 shows the optical spectrum of Ruiz 440-469B compared to that of an sdM8 subdwarf, ULAS J143517.18–014713.1 (UL1435; *Primeval IV*), and an M8 dwarf 2MASS J1434264+194050 (2M1434; Kirkpatrick et al. 1999). The S/N of Ruiz 440-469B is not good enough to distinguish the difference between an M8 and sdM8 type by the VO absorption band around 800 nm. Ruiz 440-469B has slightly bluer $J - K$ colour than normal M dwarfs on the main sequence (Fig. 1). The VISTA $J - K_s$ colour of Ruiz 440-469B (0.76 ± 0.02) is slightly bluer than that of UL1435 (0.79 ± 0.01). Therefore, Ruiz 440-469B is likely an old mildly metal-poor M8 dwarf.

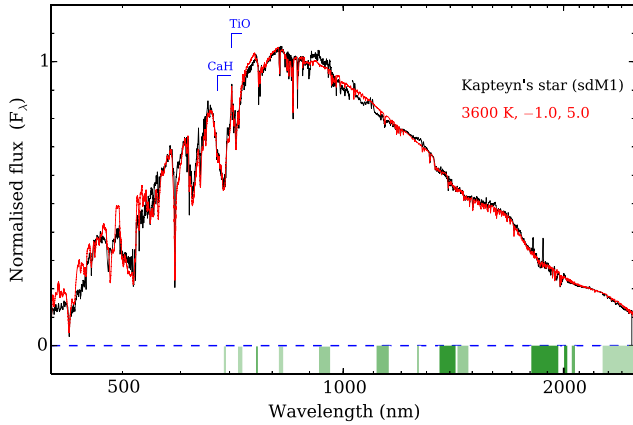
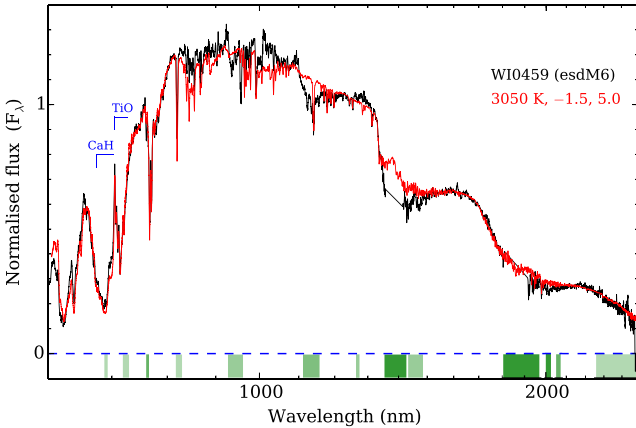
As a DA WD + M8 dwarf binary, Ruiz 440-469AB has larger total mass and closer projected separation ($8794^{+292}_{-174}\text{ au}$) than Gaia J0452–36AB. Assuming that Ruiz 440-469AB have masses of 0.5 and $0.1 M_{\odot}$, respectively. The projected separation of Ruiz 440-469AB would be around $0.067 r_J$. Therefore, Ruiz 440-469AB is also a gravitationally bound system. Properties of Ruiz 440-469AB are listed in Table 1.

5 METALLICITY CONSISTENCY OF M SUBCLASSES

Primeval I (section 4.1) noticed that the metallicity is not consistent across mid-to-late M subtypes in each metallicity subclass (sdM, esdM, and usdM) that classified by the $\zeta_{\text{TiO}/\text{CaH}}$ index (Lépine et al.

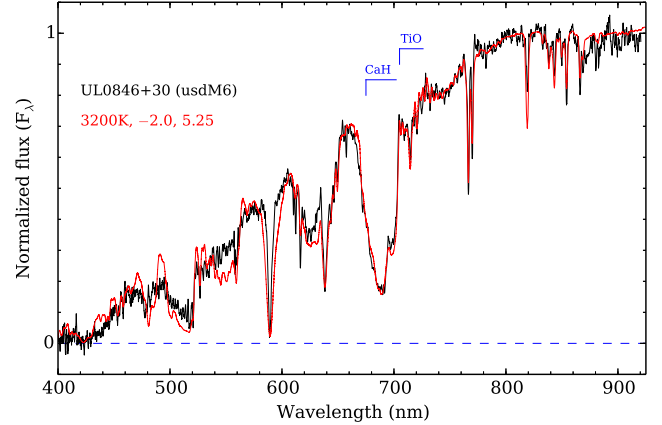
Table 2. Summary of the characteristics of the spectroscopic observations made with WHT and VLT.

Name	SpT	UT date	Telescope	Instrument/grism	Slit (arcsec)	Seeing (arcsec)	Airm	T_{int} (VIS) (s)	T_{int} (NIR) (s)
Gaia J0452–36A	esdM1	2019-02-03	WHT	ACAM/V400	1.0	1.3	2.35	600	–
Gaia J0452–36B	esdL0	2019-02-03	WHT	ACAM/V400	1.0	1.3	2.34	1200	–
Ruiz 440-469B	M8	2019-02-03	WHT	ACAM/V400	1.0	1.3	2.08	1200	–
SSSPM 1013–13	usdL0	2019-02-02	WHT	ACAM/V400	1.0	1.3	1.41	300	–
Kapteyn's star	sdM1	2016-09-14	VLT	X-shooter	1.2	1.18	1.31	2×5	2×5
WI0459	esdM6	2016-01-23	VLT	X-shooter	1.2	1.23	1.33	4×290	4×300

**Figure 6.** The X-shooter spectrum (smoothed by 51 pixels) of Kapteyn's star and its best fitting BT-Settl model spectrum with $T_{\text{eff}} = 3600$ K, $[\text{Fe}/\text{H}] = -1.0$, and $\log g = 5.0$.**Figure 7.** The optical-to-NIR spectrum of WI0459 observed with the X-shooter (smoothed by 101 pixels in the VIS and 51 pixels in the NIR). Its best-fitting BT-Settl model has $T_{\text{eff}} = 3050$ K, $[\text{Fe}/\text{H}] = -1.5$, and $\log g = 5.0$.

2007). Metallicity scale of late-type M subdwarfs are overestimated by the $\zeta_{\text{TiO}/\text{CaH}}$ index, which is also not applicable for L subdwarfs. For example, the strength of the TiO absorption band at 850 nm is not a monotonous function of metallicity for late-type M and L subdwarfs (fig. 10 in Primeval I; fig. 1 in Primeval V).

UCSDs with well-constrained metallicities are required to test the metallicity consistency of M subdwarf classification. However, the metallicity of UCSDs are extremely difficult to measure directly by observation. First because they are faint and it is difficult to observe high-quality (S/N and resolution) spectra. Secondly, they

**Figure 8.** The SDSS optical spectrum of SD0846 + 30 and its best-fitting BT-Settl model with $T_{\text{eff}} = 3200$ K, $[\text{Fe}/\text{H}] = -2.0$, and $\log g = 5.25$. The SDSS has an average resolving power of about 2000 and is smoothed by 3 pixels.

emit most of their flux at longer wavelength, and have complex molecular absorptions. Only some M0–3 subdwarfs have direct metallicity measurements based on atomic lines at blue wavelength (e.g. Woolf & Wallerstein 2005, 2006; Woolf et al. 2009). Thirdly, there are not enough wide F/G/K + M subdwarf binaries that can be used to calibrate the metallicity measurements of mid- and late-type M subdwarfs in the NIR (Rojas-Ayala et al. 2012; Newton et al. 2015).

The metallicity consistency of M subclasses can be tested with wide binaries composed of early- and late-type M subdwarfs which have the same metallicity. However, wide binary systems contain UCSDs are extremely rare. First, because UCSDs belong to rare thick disc or halo populations. Secondly, UCSDs are faint and only these in the solar neighbourhood could be well observed. Thirdly, late-type M and L subdwarfs are in a smaller mass range on the mass function compared to late-type M and L dwarfs (fig. 9, Primeval II). Lastly, some late-type M objects in the same metallicity range as early-type M subdwarfs are classified into late-type M dwarfs by the $\zeta_{\text{TiO}/\text{CaH}}$ index (Primeval I).

As a wide esdM1 + esdL0 binary, Gaia J0452–36AB is the first ideal binary that can be used to conduct a test of the metallicity consistency in the classification of UCSDs. To provide a better view of correlation between metallicity and spectral indices that used in the classification of M subdwarfs across a broad spectral type range, I collected a sample of M and L subdwarfs with known metallicity (Table 3). I studied the correlations between spectral type, metallicity ($[\text{Fe}/\text{H}]$), CaH and TiO indices, and $\zeta_{\text{TiO}/\text{CaH}}$ index based on Gaia J0452–36AB and M and L subdwarfs in Table 3.

Fig. 9(a) shows the correlations between spectral type and metallicity for M and L subdwarfs of different subclass. Metallicity

Table 3. The CaH2, CaH3, and TiO5 spectral indices (Reid et al. 1995), $\zeta_{\text{TiO/CaH}}$ index (Lépine et al. 2007), and metallicity of Kapteyn’s star, and M and L subdwarfs that are used to form the esd and usd metallicity trace lines in Fig. 9. Ref1 are references for the discoveries of these sources, and Ref2 are for spectral types (SpT) and [Fe/H].

Name	Ref1	SpT	[Fe/H]	Ref2	CaH2	CaH3	TiO5	$\zeta_{\text{CaH/TiO}}$
Kapteyn’s star	Kapteyn (1897)	sdM1	−0.99	Woolf & Wallerstein (2005)	0.651	0.816	0.830	0.567
Gaia J045238.82−361001.3	This paper	esdM1	−1.4	This paper	0.676	0.832	0.910	0.338
Gaia J045245.87−360843.8	This paper	esdL0	−1.4	This paper	0.101	0.400	0.263	0.767
G 224−58B	Zhang et al. (2013)	esdM5.5	−1.5	Pavlenko et al. (2015)	0.287	0.502	0.701	0.370
WISEA J045921.22+154059.2	Kirkpatrick et al. (2016)	esdM6	−1.5	This paper	0.274	0.471	0.412	0.705
LHS 377	Gizis (1997)	esdM7	−1.2	Primeval I	0.205	0.396	0.232	0.563
2MASS J01423153+0523285	Burgasser et al. (2004)	esdM7.5	−1.5	Primeval I	0.158	0.290	0.218	0.795
WISEA J001450.17−083823.4	Kirkpatrick et al. (2014)	esdL0	−1.2	Primeval I	0.126	0.258	0.088	0.907
2MASS J16403197+1231068	Burgasser et al. (2004)	esdL0	−1.2	Primeval I	0.113	0.244	0.078	0.909
ULAS J111429.54+072809.5	Primeval IV	esdL0	−1.4	This paper	0.129	0.276	0.124	0.877
SDSS J124410.11+273625.8	Lodieu et al. (2012)	esdL0.5	−1.5	Primeval I	0.163	0.284	0.138	0.877
ULAS J135216.31+312327.0	Primeval IV	esdL0.5	−1.6	This paper	0.130	0.270	0.119	0.880
ULAS J020858.62+020657.0	Primeval III	esdL3	−1.5	Primeval III	0.098	0.141	0.267	0.704
SDSS J084648.88+302801.7	Zhang et al. (2013)	usdM6	−2.0	This paper	0.308	0.431	0.897	0.122
APMPM J0559−2903	Schweitzer et al. (1999)	usdM7	−1.8	Primeval I	0.217	0.331	0.604	0.421
LEHPM 2−59	Burgasser et al. (2006)	usdM8	−2.2	Primeval I	0.175	0.265	0.656	0.349
SSSPM J10130734−1356204	Scholz et al. (2004)	usdL0	−1.8	Primeval I	0.114	0.204	0.248	0.734
SDSS J010448.46+153501.8	Lodieu et al. (2012)	usdL1.5	−2.4	Primeval II	0.122	0.133	0.356	0.620
SDSS J125637.16−022452.2	Sivarani et al. (2009)	usdL3	−1.8	Primeval I	0.103	0.118	0.188	0.777
2MASS J16262034+3925190	Burgasser (2004)	usdL4	−1.8	Primeval I	0.098	0.131	0.260	0.709
ULAS J230711.01+014447.1	Primeval III	usdL4.5	−1.7	Primeval III	0.069	0.145	0.282	0.687

subclasses are based on the classification schemes of Lépine et al. (2007) for early-type M subdwarfs, and Primeval I for UCSDs. The metallicity boundaries between different subclasses of M0–3 subdwarfs are derived from the correlation between [Fe/H] and $\zeta_{\text{TiO/CaH}}$ index of M0–3 subdwarfs in Fig. 9(b). The metallicity boundaries of M0–3 subclasses (Lépine et al. 2007) and UCSD subclasses (Primeval I) are roughly consistent. Objects with metallicity derived from BT-Settl models are highlighted with circles (see Table 3). These esdM and esdL subdwarfs (including Gaia J0452−36AB) are joined with blue dashed lines in orders of spectral types (primary) and metallicity (secondary). Those usdM and usdL subdwarfs are also joined with black dashed lines. They formed two metallicity trace lines along spectral subtypes in the esdM/L and usdM/L subclasses.

M subclasses are defined by ranges of the $\zeta_{\text{TiO/CaH}}$ index. M dwarfs have a mean value of $\zeta_{\text{TiO/CaH}} = 1$. The boundaries between dM, sdM, esdM, and usdM subclasses are located at $\zeta_{\text{CaH/TiO}} = 0.825, 0.5, \text{ and } 0.2$, respectively. Fig. 9(b) shows that the $\zeta_{\text{TiO/CaH}}$ index is correlated to [Fe/H] for M0–3 subdwarfs, and can be fitted with a polynomial function described as:

$$[\text{Fe}/\text{H}] = 1.949\zeta_{\text{TiO/CaH}} - 1.853 \quad (19)$$

with a root mean square (rms) of 0.252. However, the $\zeta_{\text{TiO/CaH}}$ index is not correlated to [Fe/H] for late-type M and early-type L subdwarfs. The two metallicity trace lines jump off the $\zeta_{\text{CaH/TiO}} - [\text{Fe}/\text{H}]$ correlation (equation 19) at esdM5.5 and usdM6 types, and move further away at late-type M and L types.

Fig. 9(c) shows the variation of the $\zeta_{\text{TiO/CaH}}$ index following the two metallicity trace lines across M and L spectral types. The $\zeta_{\text{CaH/TiO}}$ index is clearly not consistent across mid- and late-type M subdwarfs. Consequently, M6+ subdwarfs in the metallicity range as esdM0–5 subdwarfs would be classified into sdM and dM subclasses, and M6.5+subdwarfs in the metallicity range as usdM0–5 subdwarfs would be classified into esdM and sdM subclasses by the $\zeta_{\text{TiO/CaH}}$ index. Likewise, some late-type M subdwarfs in the

metallicity range as sdM0–5 subdwarfs would be classified into dM subclass by the $\zeta_{\text{TiO/CaH}}$ index.

Fig. 9(d) shows the two metallicity trace lines presented in Fig. 9(a) and boundaries between different subclasses in a parameter space of TiO5, CaH2, and CaH3 indices. These two metallicity trace lines follow the boundary defined by the $\zeta_{\text{CaH/TiO}}$ index for early- and mid-type M subdwarfs. However, the esd and usd trace lines turned to the left and crossed the M subclass boundaries after esdM5.5 and usdM6 types, respectively. Fig. 10 shows the same problem exist in other M subdwarf classification schemes based on CaH and TiO spectral indices (Gizis 1997; Dhital et al. 2012; Zhang et al. 2019a). Figs 9(b)–(d) and 10 show that the $\zeta_{\text{CaH/TiO}}$ index and the TiO and CaH spectral indices are temperature dependent after esdM5.5 and usdM6 types, corresponding to a mass around $0.1 M_{\odot}$ (fig. 9, Primeval II). Figs 9 and 10 show that the metallicity of each M subclass is inconsistent across mid- to late-types.

Although, the classification scheme of M subdwarfs were slightly refined a few times (Dhital et al. 2012; Lépine et al. 2013; Zhang et al. 2019a) after Lépine et al. (2007). However, the $\zeta_{\text{TiO/CaH}}$ index have small updates mostly affecting early-type M subdwarfs, and the metallicity of each subclass is still not consistent across all M subtypes. This is because UCSDs have significant different atmospheres from early-type M subdwarfs. First, dust starts to form in the ultracool atmospheres of late-type M dwarfs/subdwarfs, and have significant impact on spectral indices of UCDs/UCSDs (Jones & Tsuji 1997; Burrows & Sharp 1999). Secondly, late-type M and L subdwarfs have higher gravity than early-type M subdwarfs. Most of available oxygen would form H_2O in metal-poor atmospheres under high pressure, thus TiO reduces more rapidly with decreasing metallicity in the atmospheres of UCSDs (e.g. Reid & Hawley 2005, section 4.6.4). However, this does not affect hydride absorptions (CaH, and FeH). Therefore, the metallicity index $\zeta_{\text{TiO/CaH}}$ should not be used to classify late-type M and L subdwarfs.

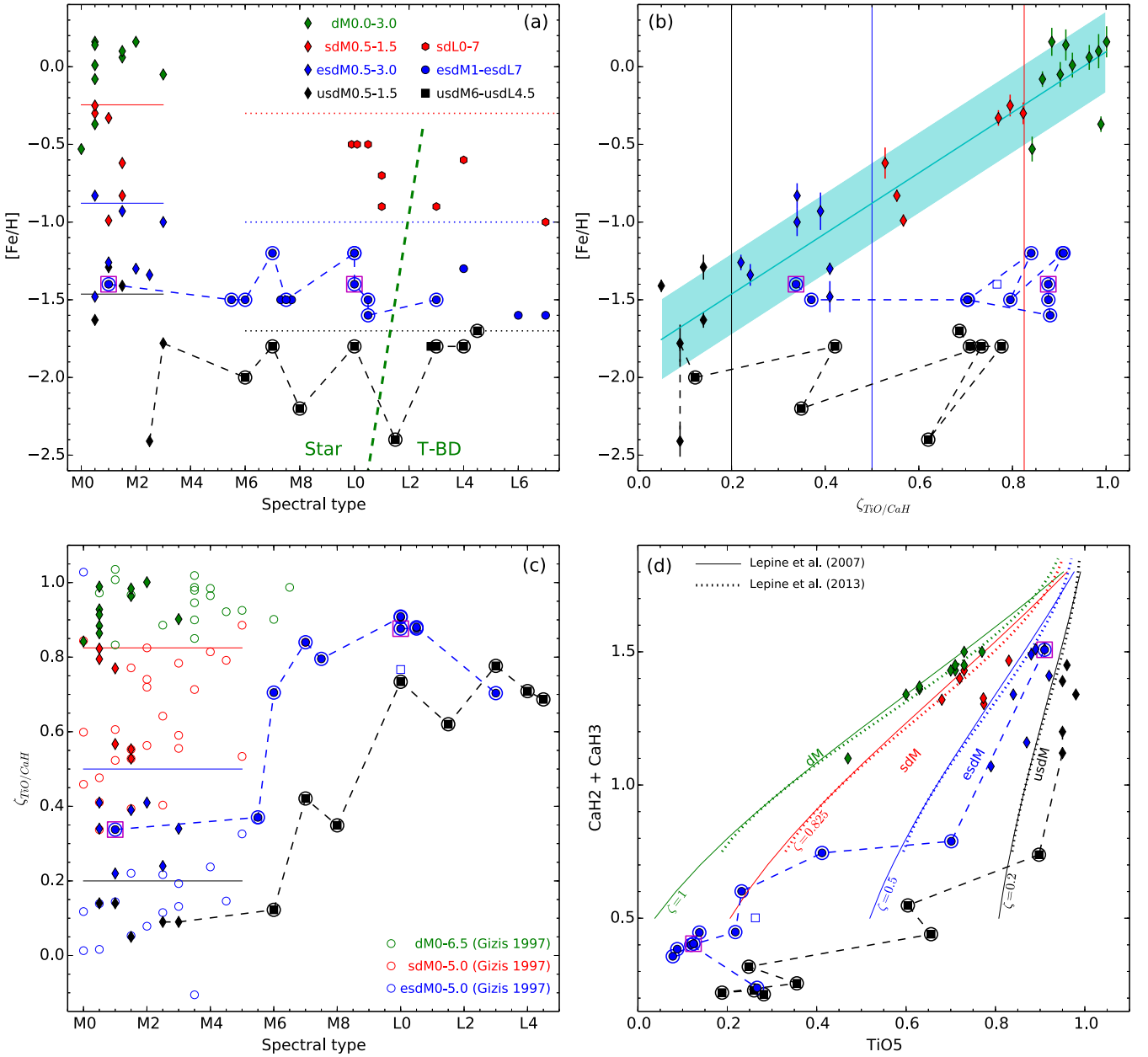


Figure 9. Spectral type, metallicity, $\text{CaH2} + \text{CaH3}$, TiO5 , and $\zeta_{\text{CaH}/\text{TiO}}$ indices of Gaia J0452-36AB, and M and L subdwarfs with known metallicities. The spectral indices of Gaia J0452-36B (blue open square) are measured from its low S/N spectrum thus have large uncertainty. UL1114 have the same spectral type and metallicity as Gaia J0452-36B thus is used as a replacement. The distance between Gaia J0452-36B and UL1114 roughly shown the index uncertainty of Gaia J0452-36B. Gaia J0452-36A and UL1114 are highlighted with magenta squares. Diamonds are M0-3 dwarfs/subdwarfs with measured $[\text{Fe}/\text{H}]$ (Woolf & Wallerstein 2005, 2006; Woolf, Lépine & Wallerstein 2009). $[\text{Fe}/\text{H}]$ of the rest M and L subdwarfs are from model spectral fittings (Pavlenko et al. 2015, Primeval I, Primeval II, Primeval III, Primeval V; This paper). Objects with known $[\text{Fe}/\text{H}]$ estimated from BT-Settl models and measured $\zeta_{\text{CaH}/\text{TiO}}$ index (see Table 3) are highlighted with open circles. Note that two pairs of them have the same spectral type and $[\text{Fe}/\text{H}]$ thus are overlapped in panel (a). Objects in esd and usd subclasses with measured spectral indices are joined separately with dashed lines in the order of spectral types. This formed two metallicity trace lines along spectral types. The red, blue, and black dotted lines in panel (a) indicate the boundaries between sd, esd, and usd subclasses of UCSDs (Primeval I). A green dashed line in panel (a) indicates an empirical boundary between very low-mass stars and T-BDs (Primeval II). The red, blue, and black solid lines in panels (b-d) indicate boundaries between dM, sdM, esdM, and usdM defined by $\zeta_{\text{CaH}/\text{TiO}} = 0.825, 0.5$, and 0.2 , respectively (Lépine et al. 2007). The dotted lines in panel (d) are for $\zeta_{\text{CaH}/\text{TiO}} = 0.825, 0.5$, and 0.2 defined in Lépine et al. (2013). The green solid and dotted lines indicate the red dwarf sequence ($\zeta_{\text{CaH}/\text{TiO}} = 1$). The cyan line and shaded area in panel (b) are the polynomial fit and fitting rms of these M0-3 dwarfs/subdwarfs (equation 19). The $[\text{Fe}/\text{H}]$ boundaries between M0-3 subclasses of Lépine et al. (2007) are indicated with red, blue, and black solid lines in panels (a) which are derived from panel (b). The green, red, and blue open circles in panel (c) are M dwarfs, and sdM and esdM subdwarfs classified by Gizis (1997).

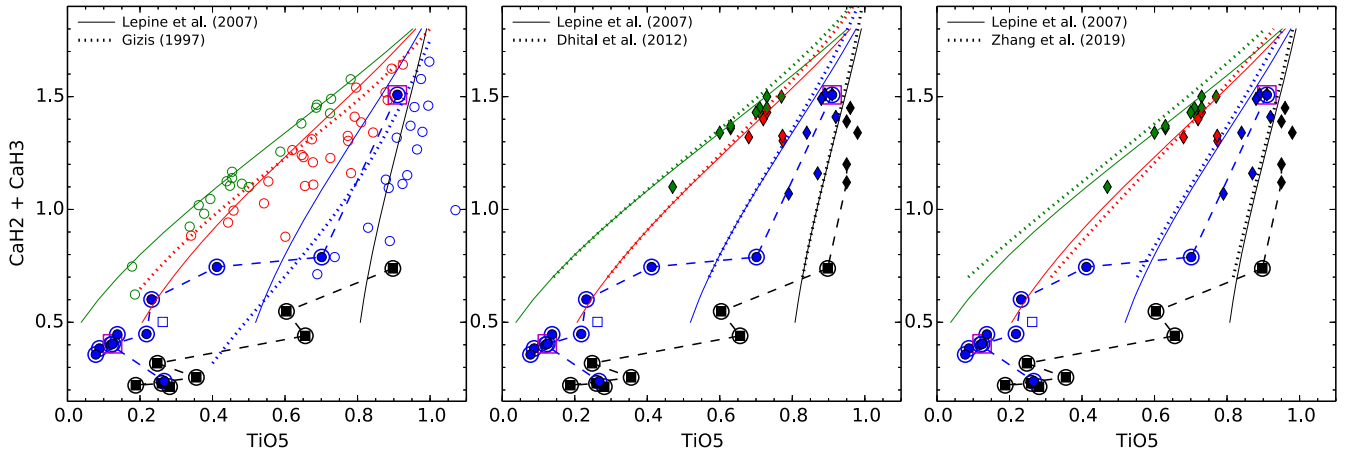


Figure 10. TiO5 and CaH2 + CaH3 indices of M subdwarf subclasses defined with the $\zeta_{\text{CaH/TiO}}$ index by Gizis (1997, left), Dhital et al. (2012, middle), and Zhang et al. (2019a, right) compared to those of Lépine et al. (2007). The red and blue dotted lines on the left-hand panel are boundaries between dM, sdM, and esdM subclasses (Burgasser & Kirkpatrick 2006) under the scheme of Gizis (1997). The other symbols are the same as in Fig. 9.

6 MASS RANGES OF M SUBCLASSES

Hydrodynamical simulations of the formation of stars and brown dwarfs in star clusters show that there is no significant dependence of stellar properties (initial mass function, binary fraction) on opacity or metallicity at $0.01\text{--}4\ M_{\odot}$ and $0.01\text{--}3\ Z_{\odot}$ (Bate 2014, 2019). However, the lack of late-type M extreme and ultra subdwarfs has been noticed (Monet et al. 1992; Gizis 1997). Zhang et al. (2013, table 9) show that the binary fraction of M subdwarfs is decreasing from the sdM to the esdM and usdM subclasses under on classification scheme of Lépine et al. (2007). These can be explained by the special properties of M subdwarfs due to low opacity and the biased spectral classification of M subdwarfs.

First, M subdwarfs under current classification scheme have lower mass ranges than M dwarfs (fig. 9, Primeval II). The maximum temperatures to form TiO, CaH, and H_2O molecules are lower at lower metallicity (e.g. fig. 9; Jao et al. 2008). At a certain mass, very low-mass stars with lower metallicity would have higher T_{eff} . Consequently, depending on the metallicity, an M0 subdwarf could have a mass up to about five times lower than a field M0 dwarf. The masses of usdM0, esdM0, sdM0 subdwarfs, and M0 dwarfs are around $0.13\text{--}0.15$, $0.15\text{--}0.3$, $0.3\text{--}0.5$, and $0.5\text{--}0.6\ M_{\odot}$, respectively. This is why M subdwarfs have much smaller radii than M dwarfs with the same T_{eff} (fig. 9; Kesseli et al. 2019). For example, the cool subdwarf component of the usdK7+WD eclipsing binary (SDSS J235524.29 + 044855.7) has mass of $0.1502 \pm 0.0017\ M_{\odot}$, radius of $0.1821 \pm 0.0007\ R_{\odot}$, $T_{\text{eff}} = 3650 \pm 50\ \text{K}$, and $[\text{Fe}/\text{H}] = -1.55 \pm 0.25$ (Rebassa-Mansergas et al. 2019). Secondly, metallicity scale of late-type M subdwarfs are overestimated by spectral indices in current classification schemes due to higher gravity and dust formation in ultracool atmospheres. Consequently, late-type M subdwarfs in the metallicity ranges of early-type sdM/esdM/usdM are classified into dM/sdM/esdM subclasses, respectively (see Section 5).

The spectral type classified by broad absorption bands (e.g. CaH, TiO; Gizis 1997; Lépine et al. 2007) in observed spectra of M subdwarfs is mainly related to their T_{eff} and metallicity. Since red subdwarfs have subsolar abundance. M subdwarfs are hotter than M dwarfs with equivalent mass (Chabrier & Baraffe 1997; Burrows et al. 2001, Primeval II). The CaH and TiO molecular bands (identification of red dwarf/subdwarfs) appear in atmospheres of red

subdwarfs at lower temperature than in red dwarfs. Consequently, M subdwarfs have much lower and narrower mass range than M dwarfs.

L subdwarfs have much narrower mass range than L dwarfs, because the corresponding spectral types of the substellar transition zone among UCSDs is from early-L to mid-T types. The spectral type (and T_{eff}) sampling from early-type L to mid-type T subdwarfs are stretched by the substellar transition zone (Zhang 2018) which covers a narrow mass range. The mass range of the substellar transition zone is between 0.065 and $0.079\ M_{\odot}$ for solar metallicity, and slightly higher but narrower at lower metallicities (fig. 5, Primeval VI).

Zhang et al. (2019a, fig.10) show that the fraction of active M subdwarfs is smaller and peaks at earlier subtypes than that of M dwarfs. This is partially due to the fact that M subdwarfs have lower mass ranges than M dwarfs. The comparison between M dwarfs and M subdwarfs is between populations in different mass ranges.

7 SUMMARY AND CONCLUSIONS

I presented the discovery of the first wide $M + L$ extreme subdwarf binary (Gaia J0452–36AB) at a distance of $137.27^{+0.68}_{-0.67}\ \text{pc}$. The binary has typical metallicity ($[\text{Fe}/\text{H}] = -1.4 \pm 0.2$) and space velocity ($U = 65 \pm 9\ \text{km s}^{-1}$; $V = -129 \pm 15\ \text{km s}^{-1}$; and $W = 42 \pm 14\ \text{km s}^{-1}$) for halo population. Gaia J0452 – 36AB is an esdM1 + esdL0 subdwarf pair with T_{eff} of 3550 ± 100 and $2600 \pm 100\ \text{K}$, respectively. Gaia J0452–36AB have masses of $0.151^{+0.029}_{-0.019}$ and $0.0855^{+0.0014}_{-0.0010}\ M_{\odot}$, respectively. Both components are very low-mass stars above the substellar transition zone at their metallicity. The binary has a projected separation of $15828 \pm 78\ \text{au}$, corresponding to 0.092 Jacobi radius, and is a gravitationally bound system.

I also presented the discovery of Ruiz 440-469B, a wide M8 dwarf companion to a cool DA white dwarf, Ruiz 440-469A. Ruiz 440-469B has slightly bluer $J - K$ colour than main-sequence stars thus maybe mildly metal-poor. Ruiz 440-469AB is at a distance of $112.94^{+3.77}_{-3.53}\ \text{pc}$ with a projected separation of $8794^{+292}_{-174}\ \text{au}$ and a tangential velocity of $112.91^{+3.77}_{-3.53}\ \text{km s}^{-1}$. Gaia J0452–36AB is also a gravitationally bound system.

Late-type M and L subdwarfs have high gravity and dust in their atmospheres which have significant impacts on the presences of CaH and TiO absorption bands. The $\zeta_{\text{CaH/TiO}}$ index is invalid for the classification of late-type M and L subdwarfs. As shown in Figs 9 and 10, the existing classification schemes of M subdwarfs performed well for M0–5 subdwarfs, but did not pass the metallicity consistency test for late-type M subdwarfs. Inconsistent metallicity across subtypes in each subclass would provide misleading information on the metallicity scale of late-type M subdwarfs.

M subdwarfs have lower and narrower mass range than M dwarfs. Because the cool subdwarfs have higher T_{eff} than dwarfs with equivalent mass, but the molecules used to define red dwarf/subdwarfs or M spectral class form at lower temperature in atmospheres with lower metallicity. The comparison between M dwarfs and M subdwarfs is between populations in different mass ranges. This partially explains the lack of late-type M extreme and ultra subdwarfs and decreasing binary fraction from sdM, to esdM and usdM subclass, in addition to the biased classification of M subdwarfs.

Red dwarfs have low masses and small radii, thus signals of RV variation and transit due to orbiting planets are relatively significant. Nearby red dwarfs became popular targets for searches of rocky exoplanets of the habitable zone. Red subdwarfs of the thick disc are in the the Galactic habitable zone (Lineweaver, Fenner & Gibson 2004) and are also good targets for exoplanet searches (e.g. Anglada-Escude et al. 2014). Mid- to late-type K subdwarfs are also in the category of very low-mass stars with mass $\lesssim 0.5 M_{\odot}$ and radius $\lesssim 0.5 R_{\odot}$, thus are also good targets for exoplanet searches with RV and transit monitoring, in addition to M subdwarfs.

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