

ON THE AGE OF THE WIDEST VERY LOW MASS BINARY

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ABSTRACT

We have recently identified the widest very low mass binary (2M0126AB), consisting of an M6.5V and an M8V dwarf with a separation of ~ 5100 AU, which is twice as large as that of the second widest known system and an order of magnitude larger than those of all other previously known wide very low mass binaries. If this binary belongs to the field population, its constituents would have masses of $\sim 0.09 M_{\odot}$, at the lower end of the stellar regime. However, in the discovery paper, we pointed out that its proper motion and position in the sky are both consistent with being a member of the young (30 Myr) Tucana/Horologium association, raising the possibility that the binary is a pair of $\sim 0.02 M_{\odot}$ brown dwarfs. We obtained optical spectroscopy at the Gemini South Observatory in order to constrain the age of the pair and clarify its nature. The absence of lithium absorption at 671 nm, modest H α emission, and the strength of the gravity-sensitive Na doublet at 818 nm all point toward an age of at least 200 Myr, ruling out the possibility that the binary is a member of Tucana/Horologium. We further estimate that the binary is younger than 2 Gyr based on its expected lifetime in the galactic disk.

Key words: stars: individual (2MASS J012655.49-502238.8, 2MASS012702.83-502321.1) – stars: low-mass, brown dwarfs

1. INTRODUCTION

Binarity is ubiquitous in stellar systems, from the most massive stars to the substellar regime. The statistical properties of binaries and higher multiple systems retain information on the physical processes that led to their formation long after they have dispersed beyond their star-forming regions. While nearly all early-B stars reside in binary systems, with a binarity fraction as high as $\sim 80\%$ (Kouwenhoven et al. 2005), this fraction falls to as low as $\sim 20\%$ (Burgasser et al. 2007) for brown dwarfs. Also, while stellar binaries are found with separations reaching 35,000 AU for early-B primaries and 20,000 AU for A primaries (Abt 1988), only a handful of substellar systems have separations beyond 200 AU. Most of these have been found in star-forming regions and open clusters, such as Oph 1623-2402 (212 AU) and Oph 1622-2405 (243 AU) in the star-forming clouds of Ophiuchus (Close et al. 2007), 2M1101-7732 (241.9 AU) in the Chamaeleon I star-forming region (Luhman 2004) and the system SE70/S Ori68, a likely 1700 ± 300 AU-wide system in the σ Orionis cluster (Caballero et al. 2006). Only three wide very low mass (VLM) binaries are known in the field, DENIS055-44 (Billères et al. 2005; ~ 220 AU), Königstuhl 1 AB (1800 ± 170 AU; Caballero 2007a) and 2M0126AB (5100 ± 400 AU; Artigau et al. 2007). Caballero (2007b) established that wide late-type binaries with a mass ratio > 0.5 are rare objects in the field, with only $1.2 \pm 0.9\%$ of VLM stars and BDs residing in such systems.

The 2M0126AB system represents the most extreme case of VLM binary known. It was discovered as a common proper motion pair by Artigau et al. (2007), and later verified by Caballero (2007a). The derived probability of having, over the whole sky, a single pair of unrelated late-Ms with matching proper motion and distances within our uncertainties is ~ 0.002 (Artigau et al. 2007); hence the two components are almost certainly gravitationally bound. Its components have spectral

types of M6.5 and M8 as confirmed by GNIRS (Elias et al. 2006) spectroscopy. While near-infrared spectroscopy shows that K I equivalent widths are compatible with those of field objects, the pair falls near the core of the Tucana/Horologium (Tuc/Hor; Zuckerman & Song 2004) association and shares its bulk motion, suggesting that 2M0126AB may be a member of this 30 Myr old moving group. If indeed it is a member of this group, the low temperatures of its components combined with a very young age would imply masses at the lower limit of the brown dwarf realm. Otherwise, if this pair is a field object (i.e., an age greater than 1 Gyr) the models of Chabrier et al. (2000) indicate masses of $0.095 M_{\odot}$ and $0.092 M_{\odot}$, close to the lower limit of the stellar regime.

Here, we present new optical spectroscopy of both components of 2M0126AB to constrain the properties of this odd pair, either as a member of a young association or as a much older field object. The wavelength interval selected contains important age or gravity indicators: the lithium feature at 670.9 nm, H α , and the 820 nm Na doublet. Observations and data reduction are described in Section 2. Results and a discussion on the physical properties constrained by these observations are given in Section 3.

2. OBSERVATIONS AND DATA REDUCTION

The data set described here was obtained with the GMOS-S spectrograph at the Gemini South Telescope on 2007 October 3. A 0.5 wide slit was used with the R400 grating and OG515 filter; the resulting resolving power was $R \sim 1900$ for a 600–950 nm wavelength coverage. The slit was aligned as to obtain a spectrum of both objects simultaneously and the observations were made using the nod-and-shuffle mode for improved sky line subtraction. Two 44.7 minute and one 12.2 minute exposures were obtained for a total integration time of 101 minutes. The observations were obtained at a mean airmass of 1.5 under photometric conditions. The exposures

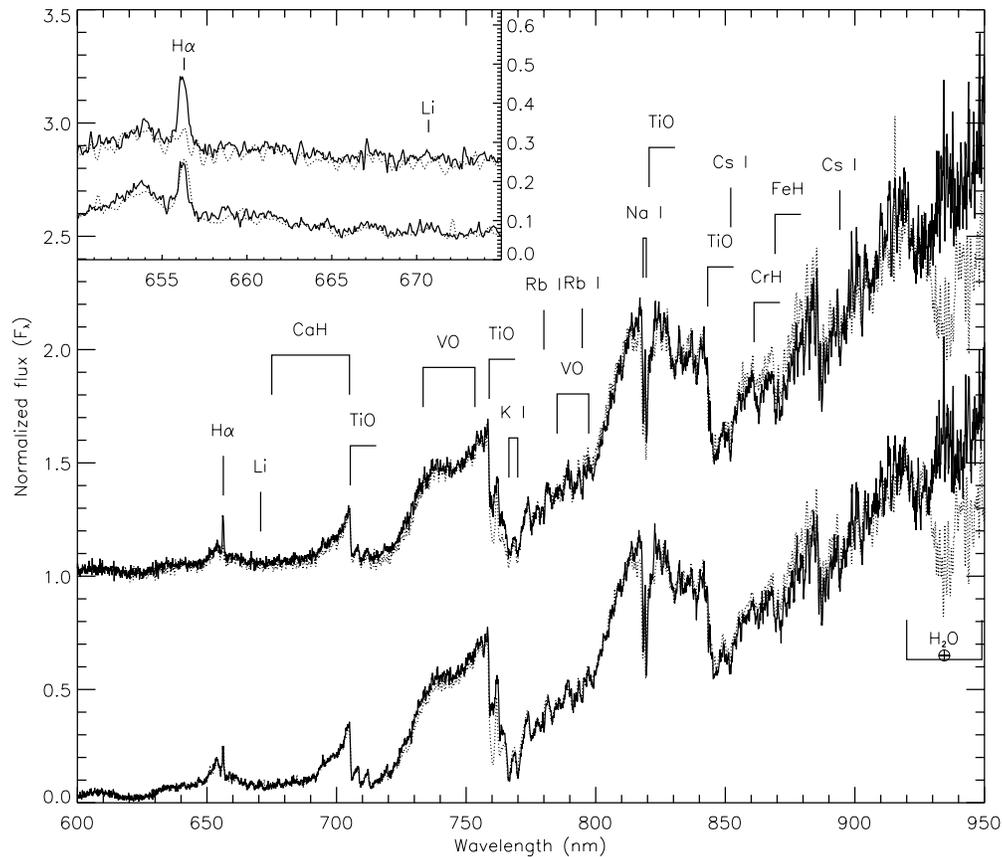


Figure 1. Spectra of 2M0126A (bottom) and 2M0126B (top, offset by +1) as well as two template objects, an M6.5 (2MASS J02422+1343, dotted line, overplotted on 2M0126A) and an M7.5 (2MASS J2585+1520, dotted line, offset by +1, overplotted on 2M0126B). All spectra have been normalized to their median flux over the 810–840 nm spectral interval. The inset shows the 650–675 nm interval that contains two important age diagnostic features, the undetected lithium line at 670.8 nm and $H\alpha$ at 656.3 nm. The inset normalization is the same as that of the main figure, but the spectra have been offset by 0.2 for clarity.

were taken at slightly different grating angles providing a spectral dithering in order to fill the 3 nm wavelength-coverage gaps caused by the spacing between the three GMOS detectors. The 790 nm, 800 nm, and 810 nm central wavelengths for each exposure displaced these gaps in the 716–740 nm and 870–882 nm intervals, i.e., in regions devoided of diagnostic spectral features. A white dwarf (EG131) was observed on 2007 September 11 with the same setup for instrumental and telluric corrections.

The individual nod-and-shuffle frames were first dark and bias subtracted. Each nod-and-shuffle frame was then calibrated using flats taken immediately before (790 nm setup) or after (800 nm and 810 nm setup) the science observation. The two nod-and-shuffle frames were then pair-subtracted, and corrected for trace distortion. Wavelength calibration was performed using copper–argon lamp spectra taken as part of the nighttime calibrations. Spectra were extracted from both the positive and the negative nod-and-shuffle traces for each component, resulting in a total of six spectra that were interpolated on a finer common-wavelength grid and median combined. The final signal-to-noise ratio (S/N) per resolution element ranges from about 15 around 650 nm to 70 around 800 nm for 2M0126A. The S/N obtained for 2M0126B is $\sim 20\%$ lower.

An image of the 2M0126AB field was taken prior to the spectroscopic observation. This 30.5 s *i*-band image used the GMOS-S central CCD without pixel binning, providing a 2.5×5.6 field of view (FOV) with a $0''.073$ pixel sampling. The image was bias subtracted, fringe corrected, and flat-fielded.

This image was used to search for additional comoving objects and test the possibility that one or both components of the system is a tight binary itself.

3. RESULTS AND DISCUSSION

Figure 1 shows the spectra of 2M0126A and 2M0126B. Both spectra show the hallmark absorption features of late-M dwarfs such as TiO, K I, and Na I. A comparison with template M6.5 and M7.5 spectra from Kirkpatrick et al. (1999) shows little difference with typical field objects, the differences around 760 nm and between 930 nm and 950 nm being due to telluric absorption (corrected in our spectra, unaccounted for in the reference spectra).

We derive an optical spectral type using the Martín et al. (1999) polynomial relations for the PC3 index for both components. These spectral types agree within 0.2 subclass to those measured in Artigau et al. (2007) and therefore we keep spectral types of $M6.5 \pm 0.5$ and $M8.0 \pm 0.5$ for our analysis. Both 2M0126A and 2M0126B show moderate $H\alpha$ emission (see inset in Figure 1) with pseudo-equivalent widths (pEW) of -3.44 \AA and -7.32 \AA , respectively. This measurement was converted into $\log(L_{H\alpha}/L_{bol})$ using the procedure described by Walkowicz et al. (2004); we obtained $\log(L_{H\alpha}/L_{bol}) = -4.5$ and -4.4 for components A and B, respectively. The measured $H\alpha$ pEW for both components are typical for objects of these spectral types (West et al. 2004). From these values alone we cannot rule out the possibility that the pair is a member of

the Tuc/Hor association as young late-Ms have widely varying levels of activity; the level observed for 2M0126A is comparable to the least active members of the 50 Myr old open cluster IC2391, while 2M0126B has $H\alpha$ strength similar to that of other late-Ms in the sample of Barrado y Navascués et al. (2004). Measurements of the $H\alpha$ pEW therefore provide little help in establishing the true nature of 2M0126AB, excluding neither of the hypotheses.

The absence of lithium absorption gives the best clue that 2M0126AB is not a member of the Tuc/Hor association (see inset in Figure 1). At a bolometric luminosity of $\log(L/L_\odot) \sim -3.1$, both objects should take 200 Myr (D’Antona & Mazzitelli 1997; Chabrier et al. 2000) to destroy lithium, implying a minimum age that is nearly an order of magnitude greater than the 30 Myr of Tuc/Hor. Kirkpatrick et al. (2006, 2008) mention that in some young objects, the lithium signature can be absent due to very low gravity and the intrinsically weaker alkali lines seen in these objects. This would explain the seemingly contradictory spectroscopic features of 2MASS J01415823–4633574: no detectable lithium at 671 nm despite numerous low gravity indicators pointing toward an age of 5–10 Myr and an estimate gravity of $\log(g) \sim 4.0 \pm 0.5$. Chabrier et al. (2000) models predict, for objects at the luminosities of 2M0126A and 2M0126B, $\log(g) = 4.2$ at an age of 30 Myr (Tuc/Hor scenario), $\log g = 5.0$ at 200 Myr (minimum age with lithium depletion), and $\log(g) = 5.3$ at 1 Gyr (half-life of the binary due to tidal disruption in the galactic disk). While the $\log(g)$ predicted for 2M0126A and 2M0126B in the Tuc/Hor scenario is close to that of 2MASS J01415823–4633574, which may cast a doubt on the validity of the lithium test in this case, we note that objects later than M5 in the 50 Myr old open cluster IC2391 do show significant lithium absorption (Barrado y Navascués et al. 2004) and that, at the same temperature as 2M0126A and 2M0126B, IC2391 late-Ms have surface gravities within about 0.4 dex of that predicted for 2M0126A and 2M0126B at 30 Myr.

The Na I doublet at 818 nm is a good gravity indicator (Kirkpatrick et al. 1991, 2006). The Na I doublet equivalent widths of $7.04 \pm 0.12 \text{ \AA}$ and $6.69 \pm 0.20 \text{ \AA}$ for 2M0126A and 2M0126B, respectively, are consistent with those of field objects but about 2 \AA larger than the values found for late-M Pleiades members (Martín et al. 1996). This indicates that both objects are significantly older than the Pleiades (130 Myr; Barrado y Navascués et al. 2004), which in turn implies surface gravities of $\log(g) > 5.0$. Such a high surface gravity further implies that the binary system would clearly show Li absorption should it be present. This confirms the lower limit on the age set by the lithium test at 200 Myr. We therefore establish that 2M0126AB cannot be a member of the Tuc/Hor association and is more likely a field pair.

Interestingly, this pair has an expected survival time in the galactic disk significantly shorter than the age of the disk itself. This timescale has been estimated by scaling to 2M0126AB the Weinberg et al. (1987) results for binaries in the solar neighborhood. With a half-life of ~ 1 Gyr, we can estimate at the 68% confidence level (equivalent to 1σ) that the pair has an age between 0.2 Gyr and 1.8 Gyr. Masses have been determined from the Chabrier et al. (2000) models for ages of 0.2 Gyr and > 1 Gyr and are given in Table 1.

We measured a list of 12 spectroscopic indices (see Table 1) compiled by Cruz & Reid (2002) in order to verify whether 2M0126AB shows any peculiarity compared to field M dwarfs. All indicators fall within the trends observed for field objects;

Table 1
Parameters of 2MASS J0126AB

Parameter	2M0126A	2M0126B
2MASS designation	J012655.49–502238.8	J012702.83–502321.1
Angular separation ^a (′)	81.86 \pm 0.10	
$\mu_\alpha \cos \delta^a$ (mas yr ⁻¹)	131 \pm 9	135 \pm 9
μ_δ^a (mas yr ⁻¹)	-53 \pm 15	-47 \pm 15
V^a	21.8	22.2
I^b	17.2 \pm 0.3	17.6 \pm 0.3
Δi_{AB}	0.518 \pm 0.015	
J^c	14.61 \pm 0.04	14.81 \pm 0.05
H^c	14.05 \pm 0.05	14.16 \pm 0.04
K_s^c	13.68 \pm 0.05	13.62 \pm 0.05
FeH 1.20 μm^a (Å)	6.0 \pm 1.8	14.5 \pm 1.9
K I 1.25 μm^a (Å)	9.8 \pm 1.1	10.3 \pm 1.0
$H\alpha$ pEW ^a	-3.44 \pm 0.40	-7.32 \pm 0.50
$\log(L_{H\alpha}/L_{bol})$	-4.5	-4.4
Li 671 nm (Å)	<0.27	<0.52
Na I EW (Å)	7.04 \pm 0.12	6.69 \pm 0.20
CaOH ^d	0.32 \pm 0.05	0.46 \pm 0.11
$H\alpha^d$	1.48 \pm 0.03	2.16 \pm 0.13
CaH1 ^{d,e}	0.87 \pm 0.07	0.94 \pm 0.11
CaH2 ^{d,e}	0.277 \pm 0.007	0.270 \pm 0.012
CaH3 ^{d,e}	0.581 \pm 0.009	0.563 \pm 0.017
TiO-a ^{d,f}	2.71 \pm 0.09	2.81 \pm 0.16
TiO2 ^d	0.32 \pm 0.02	0.33 \pm 0.03
TiO3 ^d	0.55 \pm 0.03	0.54 \pm 0.04
TiO4 ^d	0.53 \pm 0.03	0.71 \pm 0.06
TiO5 ^{d,e}	0.219 \pm 0.008	0.284 \pm 0.016
VO-a ^{d,f}	1.073 \pm 0.006	1.104 \pm 0.011
VO-b ^f	1.256 \pm 0.009	1.361 \pm 0.013
PC3 ^{d,g}	1.569 \pm 0.008	1.850 \pm 0.014
Near-IR ^a & optical SpT	M6.5V \pm 0.5	M8V \pm 0.5
Photometric distance ^a (pc)	63 \pm 5 pc	61 \pm 6
Physical separation ^a (AU)	5100 \pm 400	
T_{eff}^a (K)	2670 \pm 180	2490 \pm 180
Mass (200 Myr) ^h (M_\odot)	0.068 \pm 0.005	0.065 \pm 0.005
Mass (> 1 Gyr) ^h (M_\odot)	0.095 \pm 0.005	0.092 \pm 0.005
Age (Myr)	> 200	
M_{bol}^a	12.76 \pm 0.14	12.75 \pm 0.14
Luminosity ^a ($\log(L/L_\odot)$)	-3.21 \pm 0.05	-3.20 \pm 0.05

Notes.

^a From Artigau et al. (2007), see this reference for more details.

^b From the SuperCosmos Sky Survey catalog.

^c From the 2MASS point source catalog.

^d Cruz & Reid (2002) index.

^e Gizis (1997) index.

^f Kirkpatrick et al. (1999) index.

^g Martín et al. (1999) index.

^h Determined using the Chabrier et al. (2000) evolution models and the estimated J , H and K_s absolute magnitudes.

three are shown in Figure 2. None of the indicators deviate from the overall trends for field M dwarfs. In particular, the TiO5, being much stronger in sub-dwarfs and extreme sub-dwarfs, is a useful probe of metallicity. Our CaH1, CaH2, and CaH3 versus TiO5 measurements clearly put 2M0126A in the non-subdwarf part of Figure 1 in Gizis (1997), which extends only up to a spectral type of M7. This is in agreement with the $\lesssim 2$ Gyr age expected from dynamical considerations. Using the relations between the TiO5 and CaH2 indices versus the J -band absolute magnitude given by Cruz & Reid (2002), we derive a photometric distance of 82 ± 5 pc for 2M0126A. The photometric distance for 2M0126B cannot be easily determined through this method as the trends break for objects later than

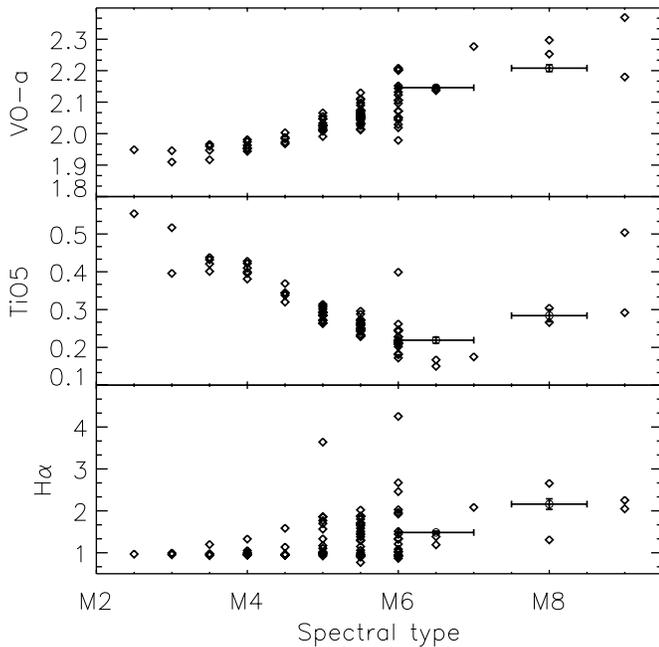


Figure 2. VO-a, TiO5, and H α indices as a function of spectral type for the Cruz & Reid (2002) sample compared to the values measured for 2M0126A and 2M0126B (data points with error bars). The values measured for our binary are consistent with the overall trends of the field M dwarf sample, indicating neither particularly large chromospheric activity nor signs of peculiar metallicity.

M7. This revised distance is somewhat larger than the distance estimated in Artigau et al. (2007) and would revise upward the physical separation of the pair to about 6700 AU. Using the Reid et al. (1995) relation the TiO5 index alone points toward a slightly earlier spectral type ($M6.0 \pm 0.5$) for 2M0126A. This mild inconsistency in the distance to 2M0126AB illustrates the need for a more reliable distance measurement based on parallax.

Using the GMOS *i*-band image of 2M0126AB, we rule out, using the subtraction of a field stars' point-spread function (PSF), that either of its components is itself an equal-luminosity binary with a separation $> 0''.2$. An object $\sim 4''$ north-west of 2M0126A was examined as a plausible close-in companion, 2.0 mag fainter than 2M0126A. This object is undetected in *J*-band images taken in 2006 June, implying a flux ratio greater than ~ 3.0 mag. This object is thus at least 1.0 mag bluer in $i_{AB} - J$ than 2M0126A and therefore cannot realistically be a later-type companion. No other object, down to a $\Delta i_{AB} \sim 4.5$ mag, is seen within $5''$ of either component. The flux ratio between 2M0126A and 2M0126B is measured to be $\Delta i = 0.518 \pm 0.015$ mag, consistent with, but much more accurate, than the SuperCosmos Sky Survey (Hambly et al. 2001) *I*-band photometry. A separation of $81''.89 \pm 0''.2$ is measured between the two components, consistent with previous measurements.

Overall, aside from the fact that they compose the widest VLM binary, 2M0126A and 2M0126B are basically indistinguishable from the bulk of field M dwarfs, in age, surface gravity, activity level, or metallicity. The fact that 2M0126AB is a relatively old system makes it all the more remarkable as compared to the bulk of wide VLM binaries found in star-forming regions. This object demonstrates that at least a handful of dynamically very fragile systems do survive to become field objects; a result that future work on the dynamics of star-forming regions will have to take into account.

The properties of 2M0126AB are interesting to compare with those of their more massive counterparts. The correlation between the upper limit on separation versus the mass of the primary ($2500 M_{\text{primary}}^{1.54}$) noted by Abt (1988) in the B5–K0 interval clearly does not hold for the system described here, where we would expect a maximum separation of about 60 AU. Interestingly, the order of magnitude of this limit is consistent with the sharp cutoff at ~ 50 AU in the distribution of VLM binaries. While the discovery of 2M0126AB shows that much wider VLM binaries exist, the next step in the study of such systems would be a census of similar systems through a dedicated survey, in which high care is taken in assessing the sensitivity and completeness limits such that clear and robust conclusions can be drawn. As these systems are likely to be very rare, a large sample of mid-to-late-Ms would be needed. It is also noteworthy that among the 500 or so L and T dwarfs in the 2MASS catalog, no binary wider than $2''$ has been identified. How rare are pairs with total masses much below that of 2M0126AB at similar separations, if they exist at all, remains to be seen.

An interesting avenue of investigation will also be to determine whether forming pairs like 2M0126AB is fundamentally different from forming VLM binaries separated by tens of AUs. One striking property of VLM binaries, as compared to stellar binaries, is the strongly peaked mass ratio distribution toward unity (Burgasser et al. 2007), with 77% of the systems having $M_2/M_1 \geq 0.8$, while late-F to K dwarfs binaries show a much flatter distribution. Interestingly, 2M0126AB has $M_2/M_1 \sim 0.95$, more in line with the VLM binary distribution. While obviously no broad-ranging conclusions can be drawn from the discovery of a single object, the discovery of only a handful of systems similar to 2M0126AB should clarify if they share the formation mechanisms of their siblings and represent the tail of the distribution, possibly dynamically excited during their formation, or if the formation scenarios themselves differ.

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