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DISCOVERY OF A WIDE COMPANION NEAR THE DEUTERIUM BURNING MASS LIMIT IN THE UPPER SCORPIUS ASSOCIATION

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ABSTRACT

We present the discovery of a companion near the deuterium burning mass limit located at a very wide distance, at an angular separation of 4.6±0.1″ (projected distance of ∼670 AU) from UScoCTIO 108, a brown dwarf of the very young Upper Scorpius association. Optical and near-infrared photometry and spectroscopy confirm the cool nature of both objects, with spectral types of M7 and M9.5, respectively, and that they are bona fide members of the association, showing low gravity and features of youth. Their masses, estimated from the comparison of their bolometric luminosities and theoretical models for the age range of the association, are 60 ± 20 and $14^{+2}_{-8}\,M_{Jup}$, respectively. The existence of this object around a brown dwarf at this wide orbit suggests that the companion is unlikely to have formed in a disk based on current planet formation models. Because this system is rather weakly bound, they did not probably form through dynamical ejection of stellar embryos.

Subject headings: stars: low-mass, brown dwarfs — stars: pre-main sequence — stars: planetary systems — binaries: general — stars: individual (UScoCTIO 108)

1. INTRODUCTION

To date, about 250 extrasolar planets have been identified using the indirect techniques of radial velocity, photometric transit and microlensing (Mayor & Queloz 1995; Konacki et al. 2003; Udalski et al. 2005). The direct detection of a planet's light allows a detailed study of its physical properties and it is crucial to improve our undestanding of these objects. At present, one extrasolar planetary-mass companion has been directly imaged around the brown dwarf 2MASS J12073347-3932540 in the very young TW Hydra association (Chauvin et al. 2004). Several substellar companions with masses close but likely above the deuterium burning mass limit (∼ 13 M_{Jup}[6], Saumon et al. 1996) have also been imaged around stellar and substellar primaries (Neühauser et al. 2005; Chauvin et al. 2005; Itoh et al. 2005; Luhman 2004; Luhman et al. 2006; Jayawardhana & Ivanov 2006; Allers 2006; Close et al. 2007). All these systems are young (< 50 Myr) and have projected separations lower than 260 AU. There are also two unconfirmed planetary candidates imaged around brown dwarfs in the σ and λ Orionis clusters (Caballero et al. 2006; Barrado et al. 2007). Here, we present the discovery of a companion near the deuterium burning mass limit located at the much wider projected separation of 670 AU from the brown dwarf UScoCTIO 108 (Ardila, Martín & Basri 2000), which belongs to the Upper Scorpius (USco) association. This is one of the youngest and closest OB associations to the Sun, located at an average distance of 145±2 pc and with an estimated age of 5–6 Myr, (de Zeeuw et al. 1999; Preibisch & Zinnecker 1999).

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[6] 1 $M_\odot$ = 1047.7 M_{Jup}

2. OBSERVATIONS

We have searched for very red and faint companions ($J >$ 16 and $J - K_s >$ 1) around 500 previously known members and candidates of the USco association (Ardila et al. 2000; Preibisch, Guenther & Zinnecker 2001; Preibisch et al. 2002; Martín, Delfosse & Guieu 2004; Lodieu et al. 2007) using the 2MASS and DENIS catalogues database and the United Kingdom Schmidt Telescope (UKST) plates. Among other candidates, we identified a red source (2MASS J16055409-1818488) in the 2MASS catalogue around UScoCTIO 108 (2MASS J16055407-1818443). Follow-up observations in the I-band showed that the new object has $I - J = 3.38 \pm 0.09$ and is located at an angular distance of 4.6±0.1″ and a position angle of 177±1°. Additional optical and near-infrared imaging and low resolution spectroscopy were carried out using different instrumentation. The detailed observing log is provided in Table 1. Weather conditions were photometric at all the observatories and average seeing was in the range 0.7–1.0″.

We reduced the data with standard techniques, using routines within the IRAF environment, including bias and flat-field correction in the optical, and sky subtraction and flat-field correction in the near infrared. Finally, we aligned and combined individual images to obtain the final one. A composite colour image using the IZK' bands of UScoCTIO 108A and B is shown in Figure 1. We have performed aperture and PSF photometry of the resulting images using the DAOPHOT package. Optical and near-infrared images have been calibrated using bright sources in common with the DENIS and 2MASS catalogues. The photometry of both the primary and the secondary are indicated in Table 2. The spectra were extracted using the APALL routine, wavelength calibrated, and corrected for the instrumental response with observations of the spectrophotometric standard stars

Wolf1346 and HZ44. Near-infrared spectra have been corrected for telluric lines by dividing them by the A3-type star HD 142613 and multiplying by a blackbody of the corresponding effective temperature ($T_{\rm eff}$) of 8500 K.

3. PHYSICAL PROPERTIES AND MEMBERSHIP OF USCO

Using the photometry from Table 2, we have determined that UScoCTIO 108A and B belong to the photometric sequence of the USco association. In Figure 2, we represent an I, $I-J$ color–magnitude diagram, where both objects are indicated by filled circles. The primary follows the sequence of previously known members (Ardila et al. 2000; Preibisch et al. 2001, 2002; Martín et al. 2004; Lodieu et al. 2007) and the secondary smoothly extrapolates it towards fainter magnitudes and redder colours. We note that UScoCTIO 108B lies on the location of isolated planetary-mass objects in the σ Orionis cluster (Zapatero Osorio et al. 2000) when they are shifted to the distance of the USco association (see Figure 2). Using the WHT and IAC80 I-band images and the astrometry provided by 2MASS, we have measured the proper motion of UScoCTIO 108A to be ($\mu_\alpha \cos\delta$, $\mu_\delta = -8\pm14, -17\pm13$) mas yr^{-1} and UScoCTIO 108B to be ($\mu_\alpha \cos\delta$, $\mu_\delta = -6\pm40, -20\pm40$) mas yr^{-1}. Both measurements are consistent with the proper motion of the USco association ($\mu_\alpha \cos\delta$, $\mu_\delta = -11, -25$ mas yr^{-1}, de Zeeuw et al. 1999), but the large error bars of the secondary prevent us from reaching any firm conclusion.

We have determined the spectral classification of UScoCTIO 108A and B by comparison with standard objects of well-known spectral type and using PC3 and PC4 indexes for the optical spectra (Martín, Rebolo & Zapatero Osorio 1996) and the water index at 1.2 μm for the infrared ones (Geballe et al. 2002). In Figure 3, we present our spectra and data of other young (Oph 1622-2405AB, KPNO Tau4) and field dwarfs (VB8, 2MASS J1439284+192915, 2MASS J1506544+132106) taken from the literature (see references in the caption of the figure). We have derived a spectral type for the primary of M7 with an error of half a subclass in both the optical and near-infrared spectra, although the bluer part of the optical spectrum seems to be of a hotter object. We estimate that the secondary is an M9.5 by comparison of the optical and J-band data with the young sources Oph 1622-2405B and KPNO Tau4, an L1 according to the pseudocontinuum index PC3 ([823–827]/[754–758] nm), and its near-infrared spectrum is similar to the L3 field dwarf 2MASS J1506544+132106. The slightly different typings may be due to the effects of a low-pressure, cool atmosphere on the various optical and near-infrared spectroscopic features. We finally adopt a classification of M9.5 for UScoCTIO 108B. The spectral types of the primary and secundary correspond to a $T_{\rm eff}$ of 2700±100 K and 2350^{+100}_{-400} K, respectively, adopting the temperature scale for high gravity field dwarfs (Dahn et al. 2002; Golimowski et al. 2004). The $T_{\rm eff}$ of UScoCTIO 108A is consistent with the $T_{\rm eff}$ calculated for both components of the low-gravity M6.5 eclipsing binary 2MASS J05352184-0546085 (2900 and 2800 K). We have computed these values from the total luminosity (estimated from the K-band magnitude, the bolometric correction from Golimowski et al. 2004, and a distance of 480 pc), the radii, and $T_{\rm eff}$ ratio given by Stassun et al. (2006).

Optical spectroscopy of UScoCTIO 108A shows spectral features characteristic of youth, such as a very strong H$_\alpha$ (equivalent width, EW $= -90 \pm 2$ Å) and He I emission lines (EW[5876Å]= -10 ± 2 Å, EW[6678Å]= -1.5 ± 0.5 Å), which indicate that the primary is still in the process of accreting from a disk. In addition, alkaline lines such as Na I and K I are weaker than their field dwarf counterparts, which is characteristic of still contracting low-gravity objects. The Li I line is also detected in absorption (EW $= 0.45 \pm 0.1$ Å), but it is slightly less intense than expected for its spectral type and youth. This could be caused by the higher continuum in this region, i.e., veiling, probably due to the accretion of material from the disk. By dividing its spectrum by that of other non-accreting M7 dwarfs, such as SOri 27 (Zapatero Osorio et al. 2002), SOri 40 (Béjar et al. 1999) and VB8 (this paper), we estimate a veiling factor ($r = F_{\rm excess}/F_{\rm photo}$) of 0.4–0.7, which gives a corrected EW(Li I) = 0.6–0.8 Å, consistent with a total preservation of this element. Optical spectroscopy of UscoCTIO 108B also shows H$_\alpha$ in emission, but this is less intense than in the primary (EW $= -15 \pm 10$ Å). The presence of this line is rare (less than 20%) in the spectra of field L dwarfs (Schmidt et al. 2007), and this could be a signature of youth. The Na I and K I lines are weaker and the TiO and VO molecular bands are more intense than expected for objects of the same spectral type in the field (see Figure 3), which are also indicative of youth. Low-gravity features are even clearer in the J-band spectra, where both the primary and secondary show weaker K lines than the late-type field dwarfs. The hydrides (FeH and CrH) also appear weaker at optical and near-infrared wavelengths in the USco objects than in the field dwarfs. This is likely related to an intense TiO absorption characteristic of low gravity, cool atmospheres (Martín et al. 1996). In summary, from optical and near-infrared spectroscopy, we may conclude that UScoCTIO 108A and B have spectral features of a very young age, which support their membership of the USco association.

We have derived the luminosity of both objects from their IJK'-band magnitudes, the bolometric correction from Dahn et al. (2002), Golimowski et al. (2004) and the USco distance modulus $m - M = 5.81 \pm 0.3$ (de Zeeuw et al. 1999). We have not applied any reddening correction to apparent magnitudes since the extinction in the USco association is found to be quite small ($A_V < 2$, Preibisch & Zinnecker 1999). We have obtained a luminosity of $\log L/L_\odot = -1.95^{+0.17}_{-0.15}$ for UScoCTIO 108A and $\log L/L_\odot = -3.14 \pm 0.20$ for UScoCTIO 108B. We can estimate the mass of the objects by comparison of the derived luminosity with predictions from theoretical models (Baraffe et al. 2003; Burrows et al. 1997). Figure 4 shows the luminosity of both objects and other very low-mass substellar companions in comparison with evolutionary models from Baraffe et al. (2003). Isochrone fitting to the more massive stars sequence suggests an age of 5–6 Myr for USco (Preibisch & Zinnecker 1999). From this estimated age, we obtain a mass of $60 \pm 10\,M_{\rm Jup}$ for the primary, i.e., within the brown dwarf domain, and a mass of $14 \pm 2\,M_{\rm Jup}$ for the secondary, i.e., at the deuterium burning mass limit. The existence of Li in very low-mass stars provide an alternative way to restrict the age of the association, because this element is destroyed very fast in their fully convective interiors. The comparison of the Li abundance in early M-type members (Preibisch et al. 2001) with theoretical spectral synthesis (Zapatero Osorio et al. 2002) indicates that most of them preserve their initial Li content. According to evolutionary models, this indicates that the age of the association is lower than 8 Myr and most likely in the interval 2–4 Myr (see Zapatero Osorio et al. 2002). In fact, the great similarity between the photometric sequences of USco and σ Orionis, which has a likely age of 3 Myr, when both star associations have been moved to the same distance, and UScoCTIO 108A being still in a strong accretion phase, also argue in favor of a younger age for the system. Adopting the wider range of ages of 1–8 Myr, we estimate a conservative wider mass range for both components: $60 \pm 20\,M_{\rm Jup}$ for the primary and $14^{+2}_{-8}\,M_{\rm Jup}$ for the secondary.

4. EVIDENCE OF BINARITY

Once we have demonstrated that UScoCTIO 108A and B are members of the USco association and we have estimated their masses, one question still remains open, which is whether the binary is physically bound or just a chance projection effect. To check this, we have estimated the probability of finding a planetary-mass member ($J > 16$) in our search within a radious of 10″around 500 members and candidates of the association. This exploration is limited by sensitivity of the 2MASS Point Source Catalogue (Cutri et al. 2003), which is $J \sim 17-17.5$. We have derived the density of such objects with a J-band magnitude in the range of 16–17.5 to be $\rho \sim 1.1\,{\rm deg}^{-2}$ from a survey (Lodieu et al. 2007) that is much deeper than 2MASS. Assuming a Poissonian distribution for the number of additional members in a given area, we can estimate this probability to be 1-P, and $P = P(x = 0) = \exp(-np)$, where P is the probability of finding no additional member, n is the number of events (500), and p is the expected number of objects in a 10″radious ($p = \rho * {\rm area} = 2.67 * 10^{-5}$), with the result that there is a probability of about 1.3% that UScoCTIO 108B is another member of the association located by chance in the direction of UScoCTIO 108A. If we consider only the probability of finding another member at the distance of UScoCTIO 108B (4.6″), this probability turns out to be lower by a factor of 4.5.

The projected separation of both components, 670 AU for the average distance to the association, is also not very common in very low-mass stars and star/brown dwarf systems, but there are some known cases at this separation and even at larger ones (see Fig. 15 from Close et al. 2007). The escape velocity from the primary at this distance is only 0.4 $\rm km\,s^{-1}$ and the gravitational bound energy of the system is 1.86×10^{33} J. Although other substellar pairs with similar mass ratio are known, the UScoCTIO 108A and B system is the widest identified so far and possibly has a lowest gravitational bound energy than any other known low-mass binary (see Fig. 16 from Close et al. 2007). Following the analytical solutions given in Weinberg et al. (1987) and Binney & Tremaine (1987), we estimate that the timescale of disruption of the system in an environment with the typical density of USco (~ 0.3 object $\rm pc^{-3}$) is a few hundred million years, which is a longer timescale than that expected for the dissipation of USco.

5. CONCLUSIONS AND FINAL REMARKS

In conclusion, we have found a $14^{+2}_{-8}\,M_{\rm Jup}$ companion to the $60 \pm 20\,M_{\rm Jup}$ brown dwarf UScoCTIO 108 at an angular separation of 4.6±0.1″ (projected distance of ∼670 AU) in the very young USco association. It seems very difficult to explain the in situ formation of this object in a disk by core accretion (Pollack et al. 1996) or disk instability (Boss 1997). Given the typical size and density profile of stellar disks, there does not seem to be enough mass at such a wide separation to form a companion of this mass, unless it has originated at a lower distance and migrated to its present location. This very low-mass substellar system has a low binding energy, implying that it is unlikely to have been ejected from a higher mass unstable multiple system (Reipurth & Clarke 2001). A more likely scenario is that the system was originated from the disruption of a more massive core (Bodenheimer 1998) in a way similar to other binary stars are supposed to be formed. If the formation of these wide and very low mass systems in the denser central part of clusters is relatively frequent, this could explain the existence of isolated planetary-mass objects as planetary-mass companions that became unbound from their primaries.

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Facilities: IAC80 (CCD), WHT (AUX, ISIS), Keck (NIRSPEC), TNG (NICS).

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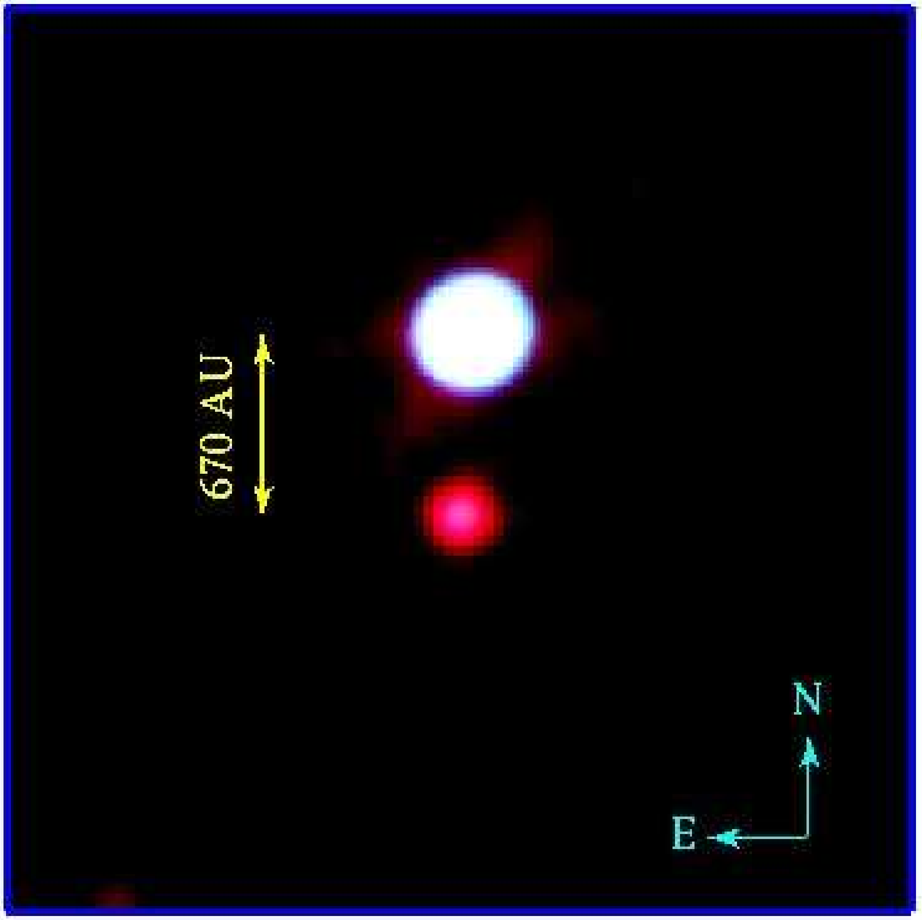

Fig. 1.— Composite colour IZK image ($19.5'' \times 19.5''$) of UScoCTIO 108A and B (I = blue, Z = green, K' = red). IZ images are from AUX intrument on the WHT and the K' image from NICS on the TNG. All images were convolved with a gaussian to a spatial resolution of $1.1''$.

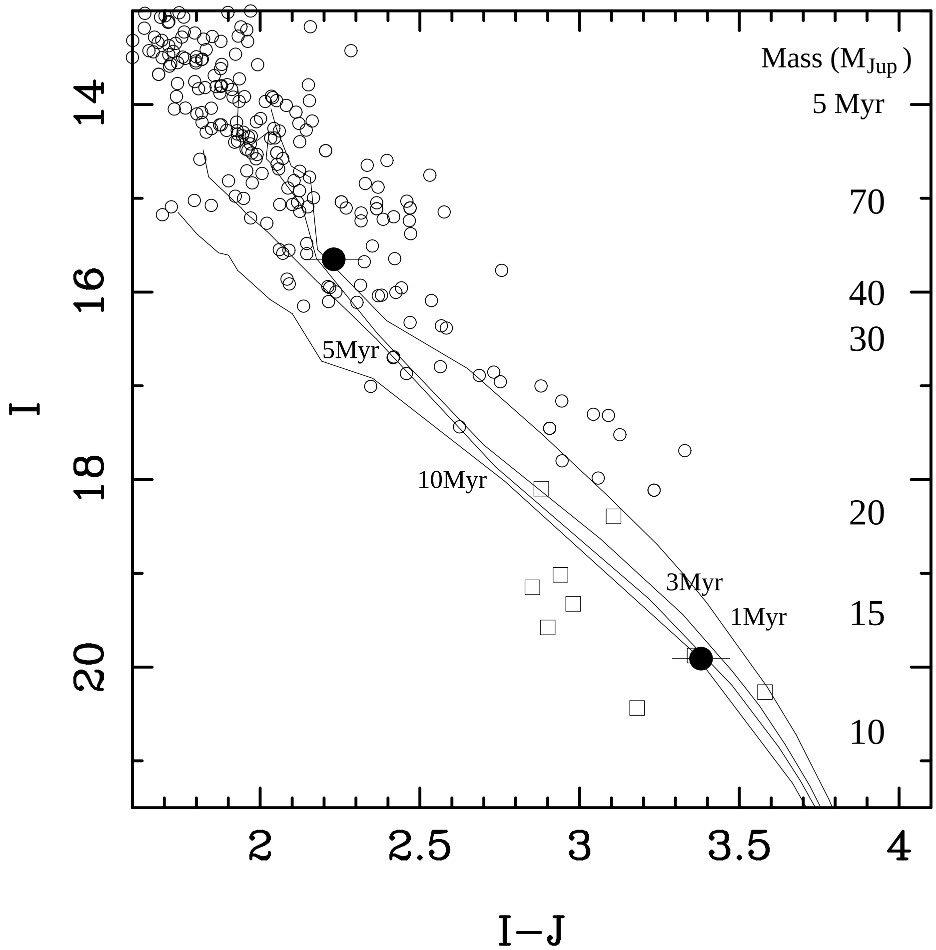

FIG. 2.— $I, I-J$ color–magnitude diagram of previously known members of the USco association (open circles) and isolated planetary-mass objects in the σ Orionis cluster (open squares) shifted to the distance of the former. UScoCTIO 108A and B are represented by solid circles with their photometric error bars. The isochrones from the Lyon group models (Baraffe et al. 2003) and estimated masses for the 5 Myr age (in Jupiter mass units) are also indicated.

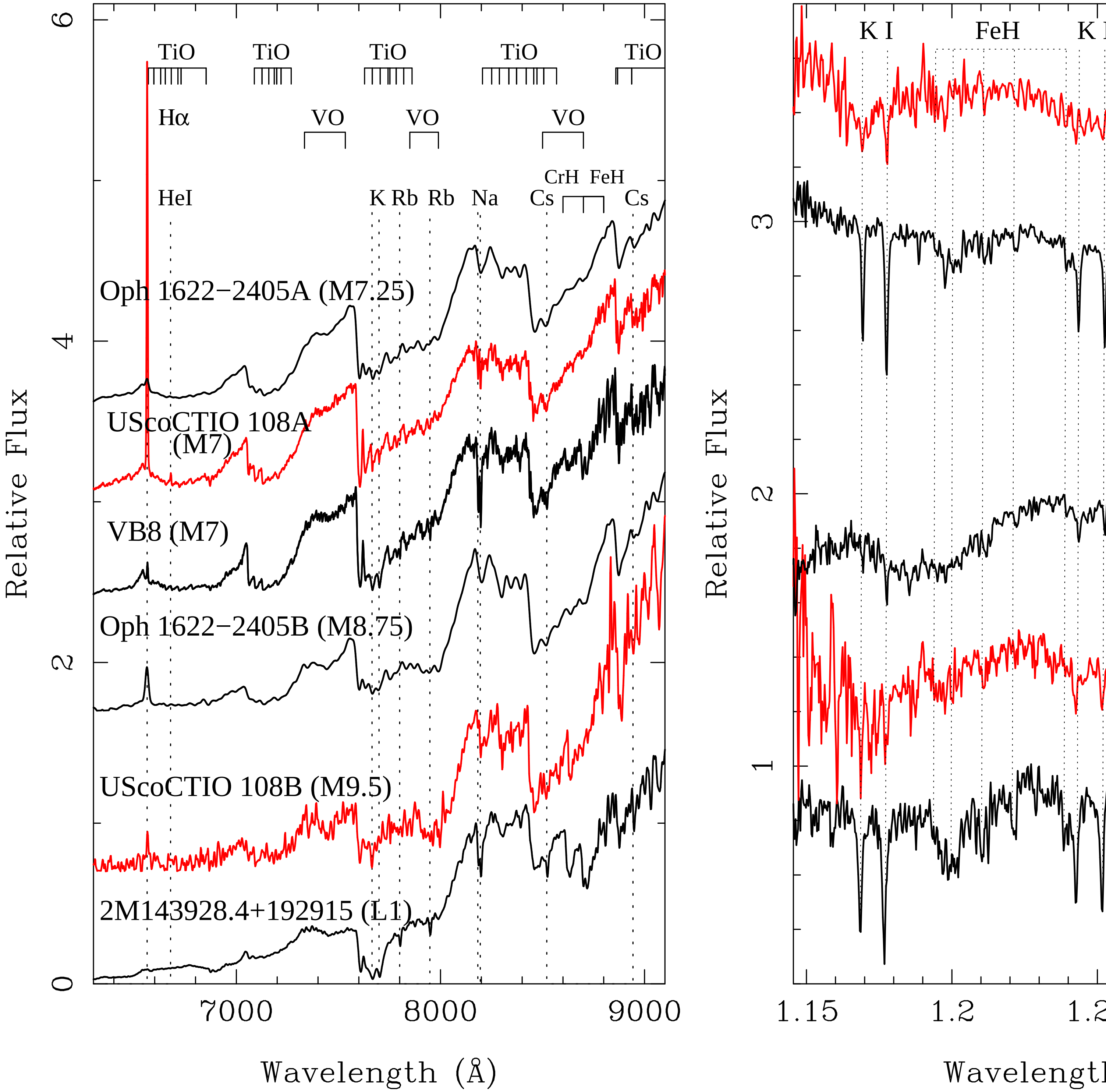

Fig. 3.— Optical (left panel) and J-band (right panel) spectra of UScoCTIO 108A and B (in red in the electronic version), young objects (data from Luhman et al. 2007 and McGovern et al. 2004) and field dwarfs (from this paper, Kirkpatrick et al. 1999, and McLean et al. 2003) of a similar spectral type. Their names, spectral type, and main spectroscopic features are indicated. All the spectra have been normalized to unity at 8175Å and 1.30 μm.

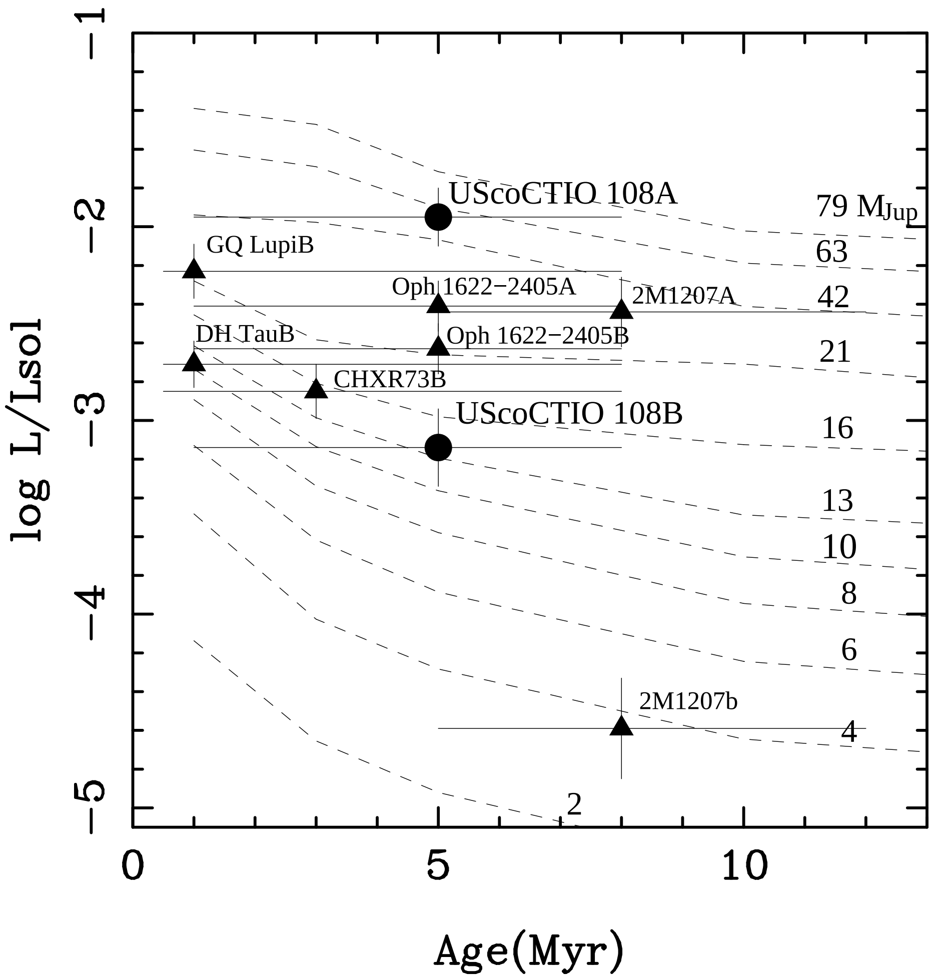

Fig. 4.— Luminosity, age diagram. UScoCTIO108 A and B, are represented by solid circles, and other very low-mass substellar companions as triangles (data from Luhman et al. 2006, 2007; Chauvin et al. 2004). Evolutionary tracks (dashed lines) from the Lyon group models (Baraffe et al. 2003) are also shown. Masses to the right are indicated in Jupiter mass units.

TABLE 1
OBSERVING LOG

Telescope	Instrument	Mode	Plate Scale ($''$ pix^{-1})	Wavelength range (μm)	Dispersion (Å pix^{-1})	Resolution (Å)	Obs. date	Exp. time (s)
IAC80	CCD (2k×2k)	Imaging	0.305	I	···	···	2007 July 5	3600
WHT	AUX (1k×1k)	Imaging	0.108	IZ	···	···	2007 July 15	600
WHT	ISIS (R158R grating)	Spectroscopy	0.22	0.55–0.95	1.8	6	2007 July 15	7200
TNG	NICS (1k×1k)	Imaging	0.25	JHK'	···	···	2007 July 16	300
KeckII	NIRSPEC	Spectroscopy	0.19	1.14–1.35	2.8	9	2007 July 24	600

TABLE 2
Photometric and spectroscopic data and physical parameters

ID	I	$I-Z$	$I-J$	$J-H$	$J-K'$	Sp. Type	Luminosity log $L/L_{\odot}$	T_{eff} (K)	Mass (M_{Jup})
UScoCTIO 108A	15.65±0.08	1.00±0.1	2.23±0.09	0.58±0.04	0.91±0.04	M7	$-1.95^{+0.17}_{-0.15}$	2700±100	60±20
UScoCTIO 108B	19.91±0.08	1.30±0.1	3.38±0.09	0.78±0.08	1.42±0.11	M9.5	-3.14±0.20	2350^{+100}_{-400}	14^{+2}_{-8}