The Wide Brown Dwarf Binary Oph 1622-2405 and Discovery of A Wide, Low Mass Binary in Ophiuchus (Oph 1623-2402): A New Class of Young Evaporating Wide Binaries?

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**ABSTRACT**

We imaged five objects near the star forming clouds of Ophiuchus with the Keck Laser Guide Star AO system. We resolved Allers et al. (2006)'s #11 (Oph 1622-2405) and #16 (Oph 1623-2402) into binary systems. The #11 object is resolved into a 243 AU binary, the widest known for a very low mass (VLM) binary. The binary nature of #11 was discovered first by Allers (2005) and independently here during which we obtained the first spatially resolved $R \sim 2000$ near-infrared (J & K) spectra, mid-IR photometry, and orbital motion estimates. We estimate for 11A and 11B gravities ($\log(g) > 3.75$), ages ($5 \pm 2$ Myr), luminosities ($\log(L/L_\odot) = -2.77 \pm 0.10$ and $-2.96 \pm 0.10$), and temperatures ($T_{\text{eff}} = 2375 \pm 175$ and $2175 \pm 175$ K). We find self-consistent DUSTY evolutionary model (Chabrier et al. 2000) masses of $17^{+4}_{-5} M_\text{Jup}$ and $14^{+6}_{-5} M_\text{Jup}$, for 11A and 11B respectively. Our masses are higher than those previously reported (13–15

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$M_{\text{Jup}}$ and 7–8 $M_{\text{Jup}}$ by Jayawardhana & Ivanov (2006b). Hence, we find the system is unlikely a “planetary mass binary”, (in agreement with Luhman et al. 2007) but it has the second lowest mass and lowest binding energy of any known binary. Oph #11 and Oph #16 belong to a newly recognized population of wide ($\gtrsim 100$ AU), young (< 10 Myr), roughly equal mass, VLM stellar and brown dwarf binaries. We deduce that $\sim 6 \pm 3\%$ of young (< 10 Myr) VLM objects are in such wide systems. However, only $0.3 \pm 0.1\%$ of old field VLM objects are found in such wide systems. Thus, young, wide, VLM binary populations may be evaporating, due to stellar encounters in their natal clusters, leading to a field population depleted in wide VLM systems.

Subject headings: instrumentation: adaptive optics — binaries: general — stars: evolution — stars: formation — stars: individual (2MASS J16222521-2405139 and 2MASS J16233609-2402209) — Brown Dwarfs — extrasolar planets

1. Introduction

The system 2MASS1207334-393254 (sep $\sim 41$ AU, 2M1207A $\sim 21M_{\text{Jup}}$, 2M1207b $\sim 5M_{\text{Jup}}$) demonstrated that very low-mass objects could remain bound for at least 8 Myr (Chauvin et al. 2004; 2005c; Mamajek 2005; Song et al. 2006). A somewhat similar very wide ($\sim 241$ AU), very young, nearly equal mass, brown dwarf binary (2MASS J1101192-773238) has been discovered in Chameleon (Luhman 2004). While Billeres et al. (2005) discovered a wide ($\sim 200$ AU), much older, field binary Denis J0551-44. They noted that ”wide ultracool binaries are undoubtedly rare in the field”. Indeed, of the $\sim 69$ field VLM binaries now known only Denis J0551-44 and Denis 2200-30 ($\sim 38$ AU) have separations wider than $\sim 30$AU (Close et al. 2003; Bouy et al. 2003; see also Burgasser et al. 2006; and Siegler et al. 2005 and references therein).

Calculations of opacity-limited fragmentation in a turbulent 3-D medium yield minimum masses $\sim 7$ Mjup (e.g., Low & Lynden-Bell 1976; Boyd & Whitworth 2005, Bate 2005 and references therein). Thus, a binary system with individual masses in the vicinity of 7 times that of Jupiter is theoretically plausible; however, it should also be very rare since even a $>5\%$ fraction of higher mass binary brown dwarfs is difficult to produce from star formation simulations (Bate et al. 2002; 2003). Jayawardhana & Ivanov (2006b) recently claimed discovery of just such a wide “planetary mass binary”. We independently discovered this very same pair ”Oph 11” in the course of our high-resolution survey of the Allers et al. (2006) Ophiuchus dark cloud low-mass objects (we note in passing that Allers (2005) was the first to resolve this system).
Allers et al. (2006) present a near-infrared (1.2, 1.6, and 2.2 \( \mu m \); hereafter NIR) imaging survey of several young star formation associations. By cross-correlation with the “Cores to Disks (c2d)” \textit{Spitzer} [3.6], [4.5], [5.8], [8.0], & [24] \( \mu m \) legacy mid-IR survey (Evans et al. 2003) of these same star formation regions, they were able to identify 19 candidate very young, low-mass, objects each of which appears to have a significant mid-IR excess in the \textit{Spitzer} dataset.

In a high spatial resolution imaging survey of the Allers et al. (2006) Ophiuchus cloud sources, we found their sources #11 & #16 to be split into 1.7 – 1.9” binaries. In sections 4.1-4.3 we prove that #11AB is a physical binary. We consider the binary nature of #16AB in Section 4.5.

While Allers et al. (2006) estimate a mass of \( \sim 9 \) Jupiters for Oph 11B, based on their optical spectra and NIR photometry, Jayawardhana & Ivanov (2006b) estimate masses of 13-15 Jupiters and 7-8 Jupiters for 11A and 11B, respectively, with the DUSTY models of Chabrier et al. (2000). We fully summarize all the recent results on Oph #11 in section 4.4.

We will show, after an analysis of each component’s luminosity, surface gravity, age, and \( T_{\text{eff}} \), that the masses of 11A and 11B are likely just above the deuterium-burning limit (\( \sim 13 M_{\text{Jup}} \)). While we find it unlikely that Oph #11 is a planetary-mass binary, we do confirm that it is unusually wide, and of extremely low-mass, with likely the lowest binding energy of any known brown dwarf binary. Oph #16 has the 4\textsuperscript{th} lowest binding energy of any known VLM system.

In section 4.6 we note that #11 and #16 join four other recently discovered young, wide, VLM binaries which, we argue, define a new class of “young, wide, VLM binaries”. We find such wide VLM systems to be very rare in the field but \( \sim 15 \) times more common in very young clusters and associations. In section 4.6.3 we suggest that stellar encounters in these clusters have the potential to break-up/evaporate these binaries.

2. OBSERVATIONS & REDUCTIONS

2.1. Imaging Oph #11 and Oph #16 at J, H, Ks, & Ls

We independently discovered the binary nature of the Oph 11 system with the Gemini NIRI camera (Hodapp et al. 2003) on July 1, 2006 (UT) in the J, H, & Ks bands (all other objects in our survey were observed with the Keck II LGS AO system). We then obtained Ls (\( \sim 3.0 \mu m \)) images with the NIRC camera on the Keck I telescope on July 7, 2006 (UT). In all cases seeing was excellent, yielding images with FWHM\(~0.3“\) in the Ks band. We
reduced these data in the standard manner (Close et al. 2002, 2003). All images were fully flat-fielded, sky and dark subtracted, bad pixel masked, aligned, and medianed.

Figures 1 and 2 and Tables 1-3 present the measured and derived characteristics of the Oph 11 and 16 binaries. Since the northern component is brighter (in the NIR) we name it Oph 11A and the apparently cooler southern component Oph 11B.

The system is also known as 2MASS J16222522-2405138 and Jayawardhana & Ivanov (2006b) refer to it as Oph 162225-240515 (and Oph 1622). We will refer to this system as Oph #11 (and as Oph 1622-2405) since it was first mentioned in the widely available literature as #11 by Allers et al. (2006) to be an interesting low-mass object (in fact it was 11B that Allers was referring to; Allers et al. 2007). The designation of Oph 1622 is inappropriate since Allers et al.’s #10, #11, #12, and #13 objects would all also be “Oph 1622” due to their similar RA.

The night of July 1, 2006 (UT) was photometric and zeropoints from photometric standards were used for calibration at J, H, and Ks. There are small ($\text{2MASS - Gemini} = -0.12 \pm 0.09, 0.16 \pm 0.10, 0.06 \pm 0.10$ mag) differences between our calibration and the J, H, and Ks fluxes of #11 in the 2MASS point source catalog. However, the $1.9''$ separation of the binary likely leads to some errors in the 2MASS $4''$ aperture photometry, and so we adopt our values (which take the separations of the binary into account) throughout the present paper.

We also analyzed the public Spitzer [3.6], [4.5], [5.8], [8.0] $\mu$m IRAC images of #11. Utilizing a custom IRAC PSF fitting program we were able to detect (for the first time) both components of the binary in all IRAC passbands (see, for example, Figure 3). In all cases a double PSF model of a $1.94''$ binary with PA=176° was a significantly better fit to the IRAC images than a single IRAC PSF.

### 2.2. NIRSPEC J and H band Spectra of 11A and 11B

Spatially resolved $J$- and $K$-band spectra of the #11 system components were obtained on August 9, 2006 with NIRSPEC in low resolution mode on the Keck II telescope (Mclean et al. 1998, 2000). We used a $0''57\times42''$ slit and the image rotator to maintain the $\sim180^\circ$ position angle with both components on the slit. The $0''57$-wide slit corresponds to 3 pixels on the detector and a nominal resolving power of R$\sim2000$. $J$-band observations utilized the NIRSPEC-3 order-sorting filter ($1.143\text{--}1.375$ $\mu$m), and $K$-band observations used the $K$ filter ($1.996\text{--}2.382$ $\mu$m). For each filter a set of four frames was obtained in an ABBA nod pattern, nodding $\sim20''$ along the slit between the A and B positions. Integration times
for each exposure were 360 seconds in the $J$-band and 180 seconds in the $K$-band. An A0V calibrator star, HIP 80224, was observed in each band for a 60 second integration at each nod position and at a similar airmass to facilitate the removal of telluric absorption features from the target spectra. Flat, dark, and arc lamp exposures were obtained with the calibration unit internal to NIRSPEC.

The NIRSPEC data were reduced using the REDSPEC code\(^7\), a package of IDL procedures developed specifically for the reduction of NIRSPEC spectra by S. Kim, L. Prato, and I. S. McLean. The reduction of low resolution NIRSPEC data with REDSPEC is described in detail in McLean et al. (2003), and summarized here. REDSPEC uses arc lamp frames to spatially and spectrally rectify the raw data and to determine a wavelength solution from observed neon and argon emission lines of known wavelengths. Following rectification, pairs of target nods are subtracted to remove background and divided by the rectified, dark-subtracted flat field. The target and calibrator spectra are extracted by summing over 9-11 rows of data centered on the peak of the trace. For the Oph 11 observations, the peaks of the traces are separated by 18 pixels, resulting in minimum contamination between components. Intrinsic spectral features of the calibrator ($\text{Pa}\beta$ at 1.282 $\mu$m in the $J$-band and $\text{Br}\gamma$ at 2.166 $\mu$m in the $K$-band) are removed by linear interpolation over the line. The calibrator spectrum is divided from the target spectrum, and the target spectrum is multiplied by a 9770 K blackbody (the $T_{\text{eff}}$ of HIP 80224) to restore the spectral slope. To produce the final spectrum, the extracted spectra from all four nods are averaged and normalized to the continuum level at a given wavelength.

The actual resolution of the observations was estimated by fitting a Gaussian to several emission lines in the raw arc lamp frames, which resulted in $R \sim 1500$ for $J$-band and $R \sim 1900$ for $K$-band. The signal-to-noise is calculated from the maximum peak-to-peak variation and estimated to be $S/N \gtrsim 100$ for each spectrum.

3. ANALYSIS

3.1. Extinction

The JHK colors from Table 1 are bluer in H-K and redder in J-H than the stellar locus of old M & L dwarfs (see Figure 4). Kirkpatrick et al (2006) discuss the peculiar shape of the H-band in the spectra of low gravity objects. These colors are not due to a highly (line of sight) extincted source since the visible spectrum of #11 was measured to be that of a young

\(^7\)See [http://www2/keck.hawaii.edu/inst/nirspec/redspec](http://www2/keck.hawaii.edu/inst/nirspec/redspec)
M9 by Jayawardhana & Ivanov (2006a) and they (as do Allers et al. 2006; 2007) find $A_V=0$ is a good fit to the system. Moreover, our own comparison of the optical spectra of 11B from Jayawardhana & Ivanov (2006b) to a young L0 (2MASS J01415823-4633574; Kirkpatrick et al. 2006) also suggests the extinction towards 11A and 11B must be very low. Consistent with a low $A_V$, we note there is little 24 $\mu$m IR cirrus in the immediate area around #11. This is not surprising as #11 is located ($\text{dist} \sim 0.5^\circ \sim 1\text{pc}$) near the edge of the $^{13}\text{CO}$ core of the $\rho$ Oph cloud, although #11 (and #16) are still inside the $\rho$ Oph survey area (and the $^{13}\text{CO}$ cloud) of Wilking et al. (2005).

### 3.2. J and K Band Spectra of 11B

From the mainly gravity independent, yet temperature sensitive, K-band CO lines (see for example Gorlova et al. 2003) we can measure $T_{\text{eff}}$ and spectral type for 11A and 11B. However, this first requires some calibrated, young, cool brown dwarfs for comparison. There does not yet exist a standard set of very young, late M/early L spectral standards. However, the young brown dwarf 2MASS J01415823-4633574 (hereafter 2M0141) has been studied with relatively high resolution spectra from 0.5-2.5 $\mu$m by Kirkpatrick et al. (2006). They find that 2M0141 is best fit by an L0 spectral type and by $T_{\text{eff}} = 2000 \pm 100 \text{K}$ and $\log(g)=4.0 \pm 0.5$ from detailed optical to NIR spectral synthesis fits. Hence, this is an obvious brown dwarf to compare our spectra to (see Figures 5–8). In addition, McGovern et al. (2004) obtained some J-band spectra of a series of young brown dwarfs with a similar instrumental configuration (hence spectral resolution) of NIRSPEC as we did. Hence, we will also compare our J-band spectra to theirs.

#### 3.2.1. The Temperature of 11B

In Figure 6 we compare 11B to 2M0141. The excellent match of 11B’s CO, NaI, CaII, and pseudo-continuum to the K-band spectrum of 2M0141 suggests an $T_{\text{eff}} \sim 2000\text{K}$ and $\sim 5\text{Myr age (log}(g)=4)$. When we compare 11B in the J-band to 2M0141 (middle trace of Figure 8), 11B appears slightly too hot for a good fit. In fact, a better fit to the J-band of 11B is the young ($5 \pm 2 \text{ Myr}$) somewhat hotter (M9) brown dwarf $\sigma$ Ori 51 (McGovern et al. 2004). Hence, it appears that in the J-band 11B appears closer to that of an M9. Uncertainty at the level of one subclass for young brown dwarfs is not unusual. Since the $T_{\text{eff}}$ for an M9 is 2300K from the temperature scale of Martin et al. (1999), 2400K from that of Luhman et al. (1999),
and 2400K from Golomoski et al. (2004) we adopt a value of 2350K for M9. So it appears 11B could be as hot as $T_{\text{eff}} = 2350\text{K}$ from its J-band spectrum (but as cool as 2000K in the K-band). Therefore, we adopt $T_{\text{eff}} = 2175 \pm 175$ (M9.5 $\pm$ 0.5) as a reasonable match to the J & K band spectra of 11B compared to other young brown dwarfs. We note this is consistent with the M9-L0 spectral type found by Jayawardhana & Ivanov (2006b) from the visible spectrum of 11B.

3.2.2. The Surface Gravity and Age of 11B

In both the J and K spectra, log($g$) appears consistent with $\sim$ 4.0 and age 5 ± 2Myr. Younger ages seem to be precluded for 11B due to the poor fit of 11B to the very young (1–2 Myr) KPNO Tau-4 brown dwarf. Since the M9.5 spectral type of KPNO Tau-4 is consistent with the M9-L0 of 11B, we reason that the very poor fit of 11B is primarily due to significantly higher gravity in 11B compared to KPNO Tau-4. Indeed it is well known that the J-band has a host of gravity sensitive features (like the KI doublets and its entire pseudo-continuum; McGovern et al. 2004), hence we can reconcile the poor fit of 11B to KPNO Tau-4 and the good fit to $\sigma$ Ori 51 by adopting an age of 5 ± 2 (hence surface gravities of log($g$) $>$ 3.75 according to the DUSTY models) for the Oph 11 system. These ages are significantly higher than the 1 Myr assumed by Jayawardhana & Ivanov (2006b).

However, older ages of $\sim$ 30Myr are very unlikely since the strength of the NaI and CaI lines in 11B (Fig. 5 & 6) are much weaker than that of GSC 8047 (a known 30 Myr old M9.5 Tuc association member; Chauvin et al. 2005b).

3.2.3. The Temperature and Age of 11A

We find 11A is consistently $\sim$200K hotter than 11B from detailed spectral synthesis modeling of the J-band and K-band spectra (section 3.3.1). Moreover, M8.5-M9.5 spectra of age 5 ± 2 Myr should be a reasonable fit to 11A’s slightly hotter spectra than the standards of Figs 5 & 7. Hence, a $T_{\text{eff}} \sim 2375 \pm 175\text{K}$ (or M9 ± 0.5) is adopted for 11A. Again our NIR spectral type is consistent with the M9 spectral type found by Jayawardhana & Ivanov (2006b) from 11A’s visible spectrum. Although it is somewhat hard to disentangle the effects of temperature and surface gravity, the similarity of 11A’s spectra to that of 11B suggests that the age of 11A is consistent with 5 ± 2 Myr.
3.3. Synthetic Spectral Fits

3.3.1. Temperatures

We consider how our adopted $\sim 5$ Myr age and M9 and M9.5 spectral type estimates compare to synthetic spectra with $\log(g) \sim 3.95$ (consistent with the DUSTY model’s 5 Myr isochrone) and $T_{\text{eff}} = 2375$K for 11A and $T_{\text{eff}} = 2175$K for 11B. In Figure 9 we compare our observed K-band spectra to synthetic spectra computed using up-to-date PHOENIX DUSTY atmosphere models (Hauschildt et al. in prep). The synthetic spectra do a reasonable job fitting NaI and CaI, whereas the CO is a little stronger in the synthetic spectra, suggesting higher temperatures for 11A and 11B. However, we note that at these gravities some over estimation of the temperatures from the synthetic CO lines were also seen in the similar case of 2M0141 (Kirkpatrick et al. 2006).

If we let $T_{\text{eff}}$ and $\log(g)$ be free parameters, the very best fit to our observed spectra with the synthetic models suggests that $\Delta T_{\text{eff}} \sim 200$K between 11A and 11B. Hence, even though there is some uncertainty in the absolute temperatures derived from these fits, we can have some confidence in a $\Delta T_{\text{eff}} = 200$K between 11A and 11B.

3.3.2. Surface Gravities

In Figure 10 the J-band is compared to synthetic spectra. In the more gravity sensitive J-band we find our adopted $\log(g) = 3.95$ for Oph 11 is slightly too low for a good fit to the observed pseudo-continuum. A slightly better fit is obtained with $\log(g) = 4.25 \pm 0.50$. However, the adopted $T_{\text{eff}} = 2375$K and $T_{\text{eff}} = 2175$K for 11A and 11B combined with $\log(g) = 3.95$ produce good agreement on the strength of the KI doublets. Hence, it appears that our adopted age of $\sim 5$ Myr (hence $\log(g) \sim 3.95$) for 11A and 11B is reasonable.

In summary, the optimal synthetic fits suggest somewhat higher gravities ($\log(g) = 4.25 \pm 0.50$) but confirm our $\Delta T_{\text{eff}} = 200$K between 11A and 11B. Our synthetic spectra preclude $\log(g) < 3.75$ and so ages $< 2$ Myr are very unlikely for Oph 11.

3.3.3. The SED of 11A and 11B and Their Thermal IR Excess

Longward of 3 $\mu$m the SED of 11A and 11B (Table 1; Fig 11) indicates substantial excess emission compared to our synthetic M9 and M9.5 ($\log(g) = 3.95$) spectra for 11A and 11B. This suggests that both 11A and 11B have circumstellar dust disks. In particular, 11B’s
excess is very strong. The discovery by Jayawardhana & Ivanov (2006b) that both 11A and 11B have strong (and broad) Hα emission suggests active accretion may be still occurring around both of these objects. While some 50±12% of young brown dwarfs have an IR excess suggesting circumstellar disks, only ∼16±6% are estimated to be actively accreting (Bouy et al. 2006b and references within). Oph #11 is the first brown dwarf binary where there is strong evidence that both components are actively accreting. Similar conclusions were drawn for the young, single, very low mass, brown dwarf Cha 110913-773444, which also has an IR-excess (Luhman et al. 2005). As noted in Section 3.1, extinction toward Oph 11 appears to be small; thus, the two dusty disks are not close to edge on.

### 3.4. Luminosity and Mass of 11A and 11B

With an Ophiuchus distance of 125±25 pc (de Geus et al, 1989), an observed $Ks = 13.92±0.05$ mag, a K-band bolometric correction of $−3.20±0.15$ mag (Golomoski et al. 2004; appropriate for M9±0.5), and noting that for an M9 star $Ks − K ∼ 0.03$ mag (Daemgen et al. 2007), we derive a photospheric luminosity for 11A of $\log(L/L_{⊙}) = −2.77 ± 0.10$. This luminosity excludes any contribution from the excess IR emission. Similarly, we find with $BC_K = −3.10 ± 0.15$ mag for an M9.5±0.5 that $\log(L/L_{⊙}) = −2.96 ± 0.10$ for 11B.

Notwithstanding some uncertainty in theoretical evolutionary tracks at such young ages, and low masses, it is reassuring that the errors between the DUSTY tracks of Chabrier et al. (2000) and the handful of dynamical mass calibrated systems are not large when accurate spectra and K band photometry are known (Luhman & Potter (2006); Close et al 2007; Stassun et al. 2006). Hence we use our system mass and the DUSTY isochrones to estimate masses for 11A and 11B. From the HR diagram in Figure 12 we see that both 11A and 11B fall close to the 5 Myr isochrone predicted by the DUSTY models. Over the suggested age range of 3−7 Myr we find estimated masses from Figure 13 of $13−21M_{Jup}$ and $10−20M_{Jup}$ for 11A and 11B, respectively. We are not the first to caution that these masses, based on theoretical isochrones at very young ages, may have unknown systematic errors. As well the range of NIR photometry from Allers et al. (2006), Jayawardhana & Ivanov (2006b), 2MASS, and our work suggests there may be some variability in the NIR photometry (which would not be surprising for a system so young).
3.4.1. Our Masses Compared to those of Jayawardhana & Ivanov

As is clear from Table 1, our $\Delta J$, $\Delta H$, and $\Delta Ks$ values are close to that found by Jayawardhana & Ivanov (2006b). Hence, we should derive similar masses based on the above technique which was similar to theirs. However, our absolute photometric calibration is closer to that of the 2MASS point source catalog. In particular, our integrated Ks flux is just 6% brighter than the 2MASS value, whereas Jayawardhana & Ivanov (2006b) find values $\sim$30% brighter. Their significantly brighter K-band gave them closer agreement to the more luminous 1 Myr DUSTY isochrone, while we are closer to the 5 Myr isochrone (see Fig 13). Whereas, Allers (2005) and Allers et al. (2006) find Ks=14.03 $\pm$ 0.03 mag for 11B, some 40% brighter than we do in this study. Hence, deriving masses primarily based on NIR luminosity for #11 may be problematic for two reasons: first, there may be an significant underestimation of mass when one uses J and H fluxes and the dusty models (Close et al. 2005; 2006); secondly, #11 may be a young variable – so even the use of the more reliable K-band luminosity (Close et al. 2005; 2007) may be misleading. Hence we will also estimate a luminosity (and distance) independent mass based on our log(g) and age estimates in the next section.

3.4.2. Masses from log(g) and $T_{\text{eff}}$

It is reasonable to assume that the age of 11A and 11B must be < 8 Myr since there is a strong IR-excess for 11B, strong H$\alpha$ emission (Jayawardhana & Ivanov (2006b)), and both 11A and 11B are a reasonable fit to the $\sigma$ Ori 51 brown dwarf whose age < 8 Myr (McGovern et al. 2004). However, our fits to the J-band of young, late M brown dwarf standards suggest that the ages must also be $>$ 2Myr (witness the very poor fit of KPNO-Tau4). Moreover, the synthetic spectral fits find log(g)> 3.75 also precluding ages < 2 Myr for either 11A or 11B. From our age, surface gravity, and temperature ranges we find masses of $17^{+4}_{-5} M_{\text{Jup}}$ and $14^{+3}_{-5} M_{\text{Jup}}$ are appropriate (see Fig. 13). Since these masses avoid some of the pitfalls of a luminosity based mass estimate we adopt these mean ($\sim$ 5 Myr) values, but we increase the uncertainty ranges to be consistent with our HR diagram masses of $13 - 21 M_{\text{Jup}}$ and $10 - 20 M_{\text{Jup}}$ for 11A and 11B. Hence our final adopted masses are $17^{+4}_{-5} M_{\text{Jup}}$ and $14^{+6}_{-5} M_{\text{Jup}}$. Since we do not include (the currently unknown) systematic errors of these models, our mass uncertainties are likely underestimates. These masses are both slightly above the $\sim$13 $M_{\text{Jup}}$ deuterium limit, and above the 14–15 $M_{\text{Jup}}$ and 7–8 $M_{\text{Jup}}$ masses found by Jayawardhana & Ivanov (2006b).
4. DISCUSSION

4.1. Are 11A and 11B Members of the Ophiuchus Cloud Complex?

Ophiuchus 11B possesses a strong mid-IR (5 & 8 μm) excess, and 11A a weaker one (see Figure 11). Mid-IR excesses are common only among stars younger than ∼8 Myr (Mamajek et al. 2004; Silverstone et al. 2006; Rhee et al. 2006 and references therein). The strong Hα emission measured by Jayawardhana & Ivanov (2006b) for 11A and 11B suggests 11 is actively accreting and associated with the molecular cloud. Indeed, Wilking et al. (2005) find active accreters (CTTSs) ranging in age from ∼0.3−10 Myr in the r ∼ 1pc area around the ρ Oph cloud (including the location of Oph11 & Oph16). Our derived 5 ± 2Myr age of 11 is consistent with Oph 11’s ∼ 0.5° (∼ 1pc) distance from the ρ Ophiuchus cloud core where active star formation is taking place. Hence, it is very likely that 11A and 11B are members of the Ophiuchus/Upper Sco sub group of the Sco-Cen OB association.

Based on the very low extinction (A_V ∼ 0 mag) to Oph#11 (despite being in the line of sight to the 13CO cloud), we suggest that Oph#11 is at a distance of ∼ 125 ± 25pc. In other words, Oph #11 is likely slightly in the front of the ∼150 pc ”halo” of ∼ 3 Myr objects around the ρ Oph cloud core, which typically have A_V > 1.5 mag (Wilking et al 2005). To be conservative we adopt distances of 100-150 pc for the system.

4.2. Do 11A and 11B Form a Common Proper Motion Pair?

We consider whether 11A might be a foreground dwarf; statistically its observed proper motion is smaller than the expected proper motion of a foreground dwarf. We can use archival POSS II images to determine if the pair’s orientation on the sky is changing (due to 11A being a relatively fast moving foreground object). The very red optical colors of 11B make it impossible to detect in the POSS II “IR” (RG715) images, only a very faint object at the current position of 11A is observed, while neither is seen in the POSS II “blue” (GG395 filter). However, both 11A and 11B appear in the RG610 POSS II “red” filter images (Fig, 14) due to their strong Hα emission (Jayawardhana & Ivanov 2006b). In the 1993.33 epoch red POSS II images the binary separation is 2.05 ± 0.20” at PA = 174 ± 6°) which may be compared to our images (Figs. 1 & 2; separation=1.943 ± 0.022”; PA=176.2 ± 0.5°).

If #11A were a field M9 dwarf with Ks=13.92 mag, then it should be at ∼ 40±5 pc. Adopting a velocity of $V_{tan}$ ∼ 30 km/s (the approximate median of late M field dwarfs; Gizis et al. 2000), would then imply a typical displacement of ∼ 2” between 11A and 11B in the epoch 1993.33 DSS images. Since this conflicts (at the ∼ 10σ level) with what is observed,
we conclude that 11A is not a foreground field dwarf. Hence, 11A and 11B very likely form
a common proper motion pair.

4.3. Are 11A and 11B Physically Bound?

Comparison of the epoch 1993.33 and current images shows that the differential displace-
ment of 11A and 11B over the last 13.22 years is only \(~ 3 \pm 5\) km/s, consistent with
expectations for a physical system this wide (estimated period (2 \pm 1) \times 10^4\) yr; Table 3).
However, since all members of the Ophiuchus association will have similar proper motions,
it is, perhaps, possible that 11A and 11B are well separated along our line of sight but, by
chance, close together in the plane of the sky.

We can estimate how likely it is to observe two very cool (late M/early L) objects within
2" of each other in a cloud like Ophiuchus. The density of such objects can be estimated for
the survey of Allers et al. (2006); in 1700 sq. arcmin they found two ~ M8-M9 objects (#11
and #12). Follow-up optical spectra by Jayawardhana & Ivanov (2006a) showed that (in the
optical) #12 appears to be a background quasar. We in fact find #12 to be a 1.3" "optical
binary" consisting of a faint z=2 QSO "12B" and a slightly brighter G-giant "12A"− from
Gemini GNIRS IFU observations). Hence, one would expect in Ophiuchus to find one late
M/early L object in every 1700 sq. arcmin. Therefore the odds of a chance alignment of two
such objects within 2" is just ~ 2 \times 10^{-6}. Thus, most probably, 11A and 11B are physically
bound.

Are they still a physically bound pair today? If they are now drifting apart at, say,
the \(~ 0.5\) km/s escape velocity of the system, then the current 237 AU projected separation
suggests that they must have been bound until just \(~ 2 \times 10^3\) years ago. In other words, to
explain the close proximity of the pair they must have been bound for > 99% of their lives
and have only just become unbound, a very unlikely scenario. It is, however, possible that
the Oph 11 system will become unbound in the future (see Section 4.6.3.).

4.4. Our Masses and Spectral Types Compared to those of Other Recent
Studies

Several groups have recently reported spectral types and masses for Oph 11AB, Allers
et al. (2007) find spectral types of M7 \pm 1 and M8 \pm 1 for 11A and 11B (from the low
resolution R\sim 300 NIR spectra of Allers 2005). They derived ages of \(~ 20\) Myr and masses
of 65 and 35 M_{jup} from dusty models. A more recent work by the same group (Luhman et
al. 2007) find types of M7.25 and M8.75 and masses $\sim 59M_{\text{Jup}}$ and $\sim 21M_{\text{Jup}}$ for 11A and 11B and, like us, they derive an age of $\sim 5$ Myr for the system.

These two studies derive earlier spectral types than our M9±0.5 and M9.5±0.5 for 11A and 11B. Part of the disagreement is due to a lack of “gold-standard” spectral templates at $\sim 5$ Myr ages. Hence, both of these studies use/compose templates of somewhat younger ($\sim 1 - 3$ Myr) ages (and with different extinction corrections) which can lead to additional uncertainty distinguishing between age and temperature effects (for example: cooler older objects have similar alkali line strengths as younger hotter objects). Moreover, there are systematic errors in the temperature scale, adding further uncertainty to the final $T_{\text{eff}}$.

Very recently Brandeker et al. (2006b) have also estimated higher masses than Jayawardhana & Ivanov (2006b) from new NIR spectra. They confirm our spectral types and temperatures (2350±150 K and 2100±100 K for 11A and 11B; compared to our 2375 and 2175 K). They derive these temperatures by a pure comparison to the DUSTY models of Baraffe et al. (2002) and the latest brown dwarf models of Burrows et al. (2006). Over an age range of 1-10 Myr Brandeker et al. (2007) find masses of $13^{+8}_{-4}M_{\text{Jup}}$ and $10^{+5}_{-4}M_{\text{Jup}}$ for 11A and 11B (slightly lower, yet consistent, with our $17^{+4}_{-5}M_{\text{Jup}}$ and $14^{+6}_{-5}M_{\text{Jup}}$ masses).

In summary, 11A is likely above the deuterium burning limit ($\sim 13M_{\text{Jup}}$) and the system age is likely closer to 5 Myr than 1 Myr. However, there is still significant disagreement as to the exact spectral type of 11A with a range of M7.25-M9 (and dusty model masses of $\sim 58 - 13M_{\text{Jup}}$). In the case of 11B there is better agreement (M8.75–M9.5; and masses of 21 – 10$M_{\text{Jup}}$). All recent studies agree that Oph 11AB is best described as a young ($\sim 5$ Myr), very wide ($\sim 240$ AU), low mass ($M_{\text{tot}} \sim 23 - 80M_{\text{Jup}}$) brown dwarf binary. Moreover, the evidence presented here indicates that the system is also a bona-fide bound binary with both members likely possessing their own accretion disks.

4.5. The Oph #16 System

We resolved Allers’ object #16 into two components at JHKs (Fig.1 & Table 2). In a similar manner as for Oph #11 we were able to estimate Spitzer [3.6], [4.5], [5.8], and [8.0] fluxes for both components (Table 2).

4.5.1. Extinction, Colors, and Spectral Types for Oph 16A and 16B

Since Jayawardhana & Ivanov (2006a) did not obtain optical spectra of #16 it is somewhat uncertain what the true spectral types for 16A and 16B are. We note, however, that
16A and 16B appear significantly more luminous and bluer (warmer) than 11A or 11B. Moreover, #16 is just 0.3° (∼0.6pc) from the Oph cloud core (D= 125 ± 25 pc), and well inside the main dark cloud containing the L1688 core. Hence, Oph 16 would likely have an age of ∼1 Myr. If this is true than we need an extinction of $A_V \sim 3 ± 1$ to have these objects fall near the 1 Myr isochrone of $\rho$ Oph. This is a reasonable extinction since Allers et al. (2006) estimated $A_V = 2$ for this object.

After correcting our NIR photometry for the $A_V = 3 ± 1$ extinction towards #16 we find (see Table 2) for 16A J-Ks=0.99 ± 0.31 which is consistent with M2-M8 spectral types (Kirkpatrick et al. 1999). Hence, we adopt its spectral type as M5.5 ± 3. Future (spatially resolved) spectroscopic observations are required to obtain better estimates for the spectral types of 16A and 16B. However, we can estimate temperatures for 16A and 16B from our dereddened NIR colors: For 16A $T_{\text{eff}} \sim 3000 ± 300$K and for 16B $T_{\text{eff}} \sim 2925 ± 300$K (Golomoski et al. 2004). In the same manner as #11, we find (with $BC_K = -2.95$) $\log(L/L_\odot) = -1.18 ± 0.10$ for 16A and $\log(L/L_\odot) = -1.47 ± 0.10$ for 16B (where $BC_K = -3.00$; Golomoski et al. 2004). The luminosity errors of #16 take into account our 1 mag of uncertainty in the extinction correction.

4.5.2. Are 16A and 16B members of the Cloud Complex?

From the location of 16A and 16B in the HR diagram of Figure 12 it is likely that both components are members of the Ophiuchus cloud (consistent with their ∼0.6 pc distance from the core). From the ∼1 Myr isochrone (in Figure 12) we estimate masses of ∼100$M_{Jup}$ for 16A (likely a VLM star) and ∼72$M_{Jup}$ for 16B (likely a high mass brown dwarf or VLM star). Allers et al. (2006) estimated a mass for #16AB of ∼110$M_{Jup}$. Spatially resolved spectra in the NIR will be needed to better constrain the ages of 16A and 16B. However, the strong mid-IR fluxes of both 16A and 16B in Table 2 suggests that 16A and 16B are both young VLM members of the Ophiuchus cloud.

4.5.3. Are 16A and 16B Bound?

We believe that 16A and 16B form a common proper motion pair since the orientation of the binary today (separation=1.696 ± 0.005″, PA=218.29 ± 1.00; Fig. 1) is consistent with its orientation in 1982.66 (separation=1.87 ± 0.2″, PA=216 ± 10°; Fig. 14). This is exactly

8 very recently Allers et al., in prep, observe and confirm these spectral types
what we would expect for a system with a very long period of $\sim 8 \times 10^3$ years (see Table 3).

Is it plausible that 16AB could be a foreground VLM binary? We estimate (in the same manner as Close et al. 2003) such a hypothetical foreground system would have a photometric distance of $\sim 10$ pc to match 16A’s brightness and very red (under reddened) magnitudes (Ks=10.56 and J-Ks=1.41). Such a VLM binary would have a period of $\sim 170$ years and so in the 23.89 years between Fig. 1 and Fig. 14 one would expect $\sim 50^\circ$ of rotation. However, over the last 23.89 years the system has only changed by $\Delta PA = 1.9 \pm 1.0^\circ$ which shows that Oph 16 is not a foreground VLM system. Moreover, the IR-excess of 16AB cannot be explained by a foreground field (old) system. In the same manner as for Oph #11 we estimate that the odds of finding two unrelated, nearly equal magnitude, low-mass, Ophiuchus members within 2$''$ of each other is less than $\sim 10^{-5}$. Hence, we conclude that Oph #16AB is a newly discovered, wide ($\sim 212$ AU), low mass ($M_{\text{total}} \sim 0.17 M_\odot$) VLM binary system in the Ophiuchus cloud complex.

4.6. Ophiuchus #11 and #16 Compared with Other VLM Binaries

Figures 15 & 16 show how Oph #11 and Oph #16 compare with other known binary systems. Oph #11 is the second least massive binary known (with $M_{\text{tot}} \sim 0.031 M_\odot$; just slightly more massive than 2M1207) and has the lowest binding energy of any brown-dwarf binary. All currently known low binding energy systems are very young ($< 10$ Myr; plotted as open circles in Figures 15 & 16). Hence, one might predict that systems like Oph #11 will tend to become unbound as they age.

4.6.1. How Common Are Very Wide Young VLM Binaries?

It is interesting to note that very wide, low-mass, binaries may not be that rare when very young. We observed four (not counting #12) of the Allers et al. (2006) Oph sample (their #8, #10, #16) and the two M8 objects (GY 264 & GY3) of Wilking et al. (2005) with Keck II LGS AO and found #11 (with NIRI) and #16 ($\sim 33 \pm 23\%$ of the sample) were binaries, and 100% of our binaries were wide.

We caution that this is a very small sample, dominated by small number statistics. Also no correction for the Malmquist bias of the Allers et al. (2006) sample has been made. Nevertheless, a significant fraction of the Allers et al. (2006) Ophiuchus sample are young, wide, VLM binaries. Moreover, Bouy et al. (2006) find in their NGS AO survey of slightly more massive binaries in the nearby Upper Sco region that 3/9 of their binaries were wide.
VLM systems. One of these binaries, Denis PJ161833.2-251750.4AB, is spectroscopically confirmed (Luhman 2005) and another, USCO 1600AB, is likely also bound (Bouy et al. 2006). In contrast HST/ACS surveys of Upper Sco (5 Myr; Kraus et al. 2005) found no young wide VLM binaries. Bouy et al. estimate (including the non-detection of Kraus et al. 2005) that (3/12) ∼ 25% of VLM binaries in Upper Sco are wide. In summary, Bouy et al. find two solid wide (> 100 AU) VLM binaries out of 40 VLM objects; hence $f_{VLM\,\text{wide}} \sim 5^{+6}_{-2}$% in the Upper Sco OB association.

The ($\gtrsim$ 4 AU) spatial resolution survey of the lower density Taurus association of Kraus et al. (2006) with HST/ACS found 2/22 VLM objects were binary, but none were wider than ∼ 6 AU. Combining our (2/6) result and the (0/22) result by Kraus et al. (2006) suggests that 2/28 VLM objects are wide binaries. Hence, $f_{VLM\,\text{wide}} \sim 7 \pm 5$% in Taurus and Ophiuchus. This is very consistent with the $5^{+6}_{-2}$% found in the Upper Sco cluster. Merging all the surveys indicates 4/68 young (< 10 Myr) VLM objects that were observed at high resolution ($sep \gtrsim 5$ AU) were found to be wide (> 100 AU) binaries. Therefore, we adopt $f_{VLM\,\text{wide}} \sim 6 \pm 3$%. While even larger surveys with LGS AO and HST will be required to confirm these frequencies, it is clear that a significant (∼ 6%) fraction of young VLM objects are formed in wide (> 100 AU) binaries.

4.6.2. Is There a Dearth of Wide VLM Binaries in the Field?

In this section we try to estimate the frequency of wide VLM binaries in the field ($f_{VLM\,\text{wide\,old}}$) based on published surveys. After correcting for the selection effect that field objects are fainter than young objects of a given mass, we can derive the depletion of old field wide systems to that of young systems. We define $X_{\text{evap}} = f_{VLM\,\text{wide\,young}} / f_{VLM\,\text{wide\,old}}$, as the fraction of wide VLM binaries that have “evaporated” as these binaries age.

Of the 69 field (old; 0.5–10 Gyr) VLM ($M_{\text{tot}} < 0.2M_\odot$) binaries currently known (VLM Binary Archive $^9$) only Denis 0551 is wider than 100 AU. Hence only ∼ 1.4% of known field VLM binaries are wide. All searches to find wide VLM binaries (Close et al. 2003; Gizis et al. 2003; Bouy et al. 2003; Burgasser et al. 2003; Siegler et al. 2005; Allen et al. 2007; Reid et al. 2006; Burgasser et al. 2006 and references within) have all failed to find a single wide (> 50 AU) VLM field binary despite being sensitive to $sep \gtrsim 2$ AU and masses $\gtrsim 13M_{\text{jup}}$. The 132 VLM (M7-L8) study of Allen et al. (2007) alone suggests the frequency of wide VLM systems must be $f_{VLM\,\text{wide\,old}} < 2.3$% in the field at the 95% confidence level.

$^9$http://paperclip.as.arizona.edu/~nsiegler/VLM_binaries
Maintained by Nick Siegler
Only the seeing limited survey of Billeres et al. (2005) found one wide system: Denis 0551. While it is difficult to estimate the total number of unique VLM objects searched we note that Close et al. 2003 & Siegler et al. imaged 80 M6-L0 systems with AO; Reid et al. 2006 looked at 52 L dwarfs and Burgasser et al. 2003 looked at 10 T dwarfs with HST; Allen et al (2007) has looked at 123 M7-L8 systems. Hence out of \( \sim 265 \) unique VLM objects (this is a lower limit since not all studies publish their null results), none were in wide binaries. Hence we can estimate an upper limit to \( f_{\text{VLM wide}} < 1/265 = 0.37\% \). The lower limit to frequency can be bounded by the fact that one wide system exists, hence of the 580 L & T field dwarfs known (Dwarf Archives\(^{10}\)), only one is a wide binary, so \( f_{\text{VLM wide}} > 1/580 = 0.17\% \). Hence we adopt \( f_{\text{VLM wide}} \sim 0.3 \pm 0.1\% \). This is much smaller than our young wide VLM frequency of 6\% ± 3\%. While a more careful analysis of the problem is warranted, it is still clear that the frequency of wide (> 100 AU) VLM binaries (\( M_{\text{tot}} < 0.2M_{\odot} \)) is \( \sim 20^{+25}_{-13} \) times higher for young (< 10 Myr) VLM objects than for old field VLM objects.

A small observational selection effect is that a much older (\( \sim 5 \) Gyr) analog of Oph#11B maybe too cool (very late T or “Y” spectral type) and too faint to be easily detected in the field today. However, older Oph#16AB, Denis 1618AB, and USCO 1600AB systems in the field would be detected by the 2MASS survey as L dwarf primaries with L or early T dwarf secondaries (detectable by the aforementioned VLM binary surveys). Correcting for this selection effect (throwing out Oph#11) yields a slightly smaller “field detectable” wide VLM binarity of \( 3/68 = 4.4 \pm 2.5\% \) and hence a corrected \( X_{\text{evap}} = 15^{+20}_{-10} \). The lack of old wide systems is real, it is not a selection effect of our wide young binary population being too low in mass to be detected in the older field.

4.6.3. Do Wide VLM Binaries Evaporate as they Age?

One amelioration of the low (\( \sim 0.3 \pm 0.1\% \)) wide binary frequency in the field and the higher frequency of young (< 10 Myr) wide VLM binaries is that these wide VLM systems are dynamically dissipating, or evaporating, over time. After all, a differential “kick” of order \( V_{\text{esc}} \sim 1 \) km/sec would be more than adequate to dissolve all the wide VLM binaries in Figure 15.

Why would such a tidal kick occur? Over the lifetime of a wide binary there will be many smaller stochastic encounters (with other stars or molecular clouds; Weinberg et al.\(^{10}\))

\(^{10}\)http://spider.ipac.caltech.edu/staff/davy/ARCHIVE/
Maintained by Davy Kirkpatrick, Chris Gelino, & Adam Burgasser
which can increase the separation of a wide binary slowly over time. Eventually, these encounters may also disrupt the binary.

However, it is not certain by which mechanism VLM binaries will become unbound. Separations of $\sim 200$ AU are still very small compared to the average $10^{5-6}$ AU separations between stars in the galaxy (whereas wide stellar mass binaries have separations of $\sim 10^4$ AU, and so are more easily disrupted). Hence, the odds of any one encounter being close enough ($\lesssim 240$ AU) to tidally dissolve a wide (200 AU) VLM binary are very low (Close et al. 2003; Burgasser et al. 2003) unless the stellar density is high.

To investigate the stability of wide binaries we note that Weinberg et al. (1987)’s analytic solution of Fokker-Planck (FP) coefficients describing advective diffusion of a binary due to stellar encounters is

$$t^* (a_0) \sim 3.6 \times 10^5 (n_\star/0.05pc^{-3})^{-1} * (M_{tot}/M_\odot) * (M_\star/M_\odot)^{-2} * (V_{rel}/20km/s^{-1}) (a_0/AU)^{-1} \text{Gyr}$$

where $t^*(a_0)$ is the time required to evaporate a binary of an initial semi-major axis of $a_0$, the number density of stellar perturbers is $n_\star$ of mass $M_\star$ and relative velocity $V_{rel}$ (adopted from Weinberg (1987); assuming, as they do, that their $\ln \Lambda \sim 1$). Hence, the maximum projected separation of a bound binary (assuming semi-major axis $a = 1.26 \times sep$; Fischer & Marcy 1992) after 10 Gyr in the field is given by:

$$sep_{\text{diffusive}}^{\text{field}} \lesssim 28 \times 10^3 \left( \frac{0.16}{0.05pc^{-3}} \right)^{-1} \left( \frac{M_{tot}}{M_\odot} \right) \left( \frac{0.7}{M_\odot} \right)^{-2} \sim 1800 \left( \frac{M_{tot}}{0.1M_\odot} \right) \AU$$ (1)

where we have used the measured Galactic disk mass density of $0.11M_\odot/pc^{-3}$ and an average perturber mass of $0.7M_\odot$, and $V_{rel} \sim 20 \text{ km/s}$ (Pham et al. 1997; Holmberg & Flynn 2000).

In addition to the evaporation of binaries due to diffusion there is also the chance of a catastrophic encounter evaporating the binary. While such encounters are less important than diffusion, they cannot be completely ignored. From the work of Weinberg et al. we find the maximum projected separation ($sep$) of a binary to stay bound w.r.t. close encounters over 10 Gyr in the field is:

$$sep_{\text{catastrophic}}^{\text{field}} \lesssim 52 \times 10^3 \left( \frac{0.16}{0.05pc^{-3}} \right)^{-1} \left( \frac{M_{tot}}{M_\odot} \right) \left( \frac{0.7}{M_\odot} \right)^{-2} \sim 3300 \left( \frac{M_{tot}}{0.1M_\odot} \right) \AU$$ (2)

It is clear that all field VLM binaries with $M_{tot} \gtrsim 0.1M_\odot$ will be stable against any type of stellar encounter as long as $sep \lesssim 1800$ AU. To better illustrate these regions of stability we plot the above two relations on the right-hand side of Figure 17. Note how in Fig. 17...
all the VLM binaries are not in the “Field Unstable” region (since $sep << sep^\text{diffusive}_\text{field} < sep^\text{catastrophic}_\text{field}$). Therefore, we can conclude that no known VLM binary will be evaporated due to random stellar encounters in the field. However, these limits do help us understand the distribution of wide stellar mass binaries like those of Close et al. 1990 (solid triangles in Figure 17). Indeed no stellar binaries are observed in the “Field Unstable” region as one would expect.

This still leaves us with the problem of why $X_{\text{evap}} \sim 15^{+20}_{-10}$. Besides being young, all the known wide VLM systems are in the Chamaeleon I (2M1101), or Ophiuchus/Upper Sco/Sco-Cen OB (Oph 11, Oph 16, Denis 1618) clusters. Since 2M1101 is near the lower core of Chamaeleon I, with $\sim 100$ members with a core radius of $\sim 0.25$pc (Luhman 2004) we estimate that near 2M1101 $n_\ast \sim 1500/pc^3$. For the Ophiuchus core there are $> 200$ members within a radius of $\sim 0.3$ pc (Wilking et al. 2005) and so $n_\ast \sim 1800/pc^3$. At the distance of Oph#11 and Oph#16 there are $\sim 100$ more members but the density drops to $n_\ast \sim 50 - 220/pc^3$ (Wilking et al. 2005). In summary, we adopt a mean $n_\ast \sim 1000/pc^3$ for these “clusters” (in general agreement with other similar sized clusters; Gutermuth et al. 2005). These “clusters” (or associations) are much higher densities than the field. It is also true that the encounters have much longer interactions timescales (since $V_{rel} \lesssim 3$ km/s), hence the clusters where these stars formed will play a role in evaporating them before they can join the field. If we assume that these objects are subjected to an additional $\sim 10$ Myr of the mean cluster density then from the above equations we have:

$$sep^\text{diffusive}_\text{cluster} \lesssim 28 \times 10^3 \left( \frac{1000}{0.05 pc^{-3}} \right)^{-1} \left( \frac{M_{\text{tot}}}{M_\odot} \right) \left( \frac{0.7}{M_\odot} \right)^{-2} \left( \frac{3}{20 \text{km/s}} \right) \sim 44 \left( \frac{M_{\text{tot}}}{0.1 M_\odot} \right) AU$$ (3)

In the case of a catastrophic encounter we have:

$$sep^\text{catastrophic}_\text{cluster} \lesssim 52 \times 10^3 \left( \frac{1000}{0.05 pc^{-3}} \right)^{-1} \left( \frac{M_{\text{tot}}}{M_\odot} \right) \left( \frac{0.7}{M_\odot} \right)^{-2} \left( \frac{3}{20 \text{km/s}} \right) \sim 80 \left( \frac{M_{\text{tot}}}{0.1 M_\odot} \right) AU$$ (4)

Hence, after just 10 Myr the cluster has a much more disruptive effect on the wide VLM binaries than do encounters in the field over 10 Gyr. From Figure 17 we see that all known wide ($sep > 100$ AU) young ($< 10$ Myr) VLM binaries are found in the “Cluster Unstable” region where $sep^\text{diffusive}_\text{cluster} \lesssim sep \lesssim sep^\text{diffusive}_\text{field}$. Therefore, there is a good chance that all the known wide, young, VLM binaries are in the process of evaporating in their clusters. Indeed past cluster member (non-catastrophic) encounters may have already played a role
in creating the current (very wide) separations observed for this handful of objects.

Our simple analysis above is useful but approximate. However, an independent analytic solution of this problem by Ivanova et al. (2005) and Brandeker et al. (2006) implies that a $M_{\text{tot}} < 0.1M_\odot$ binary is “soft” if $a > 64$ AU. Hence, all our wide, young, VLM systems can be evaporated by a strong encounter. The timescale for such an encounter by their equations is larger than found above (our equation 4), yet their solutions still predict that Oph 11 would become unbound in $\sim 11$ Myr similar to our expectations above.

Of course none the analysis above implies that all these binaries must evaporate, only that it is possible. A more detailed numerical analysis of each system, in each cluster, would have to be carried out to ascertain individual outcomes. Indeed some of these may escape their cluster before evaporation (as may have been the case for Denis 0551).

If we assume that $\sim 10\%$ of VLM objects form in very low mass groups ($n_s \lesssim 10/pc^3$), then their wide systems will likely survive (whereas none survive for the 90% formed in clusters). Then roughly $\sim 6 \pm 3\%$ of these isolated VLM objects should be in wide systems. Hence, one expects $\sim 0.6 \pm 0.3\%$ of the field to be composed of wide VLM systems. Since this is consistent with our observed value of $f_{\text{VLM\,wide\,old}} \sim 0.3 \pm 0.1\%$ we can take some comfort that the above argument might naturally explain why $X_{\text{evap}}$ is observed to be $15^{+20}_{-10}$.

Our scenario does predict that once the system’s birth clusters themselves dissolve that $F_{\text{VLM\,wide}} \sim F_{\text{VLM\,wide\,old}}$. In other words, once the VLM binaries leave their clusters, the fraction of wide VLM binaries is “frozen” at the $F_{\text{VLM\,wide\,old}} \sim 0.3 \pm 0.1\%$ level. We can test this prediction by looking in low density open clusters of intermediate ages to test if $F_{\text{VLM\,wide}} \sim 0.3 \pm 0.1\%$. The ideal cluster for such a search would be the Pleiades (age $\sim 120$ Myr; $d \sim 120$ pc). Several large HST & AO surveys have failed to detect a single wide VLM binary in this cluster (Martin et al. 2003; Bouy et al. 2006c). A similar lack of wide system have been found in the older Hyades (Siegler et al. 2003). So by $\sim 100$ Myr there is some evidence that the wide binary population has mainly been evaporated, as Figure 17 and equations 3 & 4 would predict.

For completeness we note that disruption by molecular clouds does not likely play a significant role, since the critical FP impact parameter $b^{\text{GM\,MC}}_{FP} \sim 1 \times 10^5$ AU which is too wide to effect $\sim 200$ AU VLM binaries. However, the much wider ($\sim 2 \times 10^4$ AU) stellar mass binaries are certainly affected by molecular clouds and their $R \sim 2 – 3$ pc sub-clumps (Weinberg 1987), but they are not relevant in the VLM regime.
5. Conclusions

We have obtained the first spatially resolved $R \sim 2000$ near-infrared (J & K) spectra, mid-IR photometry, and orbital motion estimates for the wide brown dwarf binary Oph #11 (Oph 1622-2405). We estimate for 11A and 11B gravities ($\log(g) > 3.75$), ages ($5 \pm 2$ Myr), luminosities ($\log(L/L_\odot) = -2.77 \pm 0.10$ and $-2.96 \pm 0.10$), and temperatures ($T_{\text{eff}} = 2375 \pm 175$ and $2175 \pm 175$ K). We find self-consistent DUSTY evolutionary model (Chabrier et al. 2000) masses of $17^{+4}_{-5} M_{\text{Jup}}$ and $14^{+6}_{-5} M_{\text{Jup}}$, for 11A and 11B respectively. Our masses are higher than the previously reported $13-15 M_{\text{Jup}}$ and $7-8 M_{\text{Jup}}$ masses of Jayawardhana & Ivanov (2006b). Hence, we find the system is unlikely a “planetary mass binary”, but it has the second lowest mass and lowest binding energy of any known binary.

The #16 binary (Oph 1623-2402) is also an unusually wide (projected separation of 212 AU), very low-mass (VLM), binary composed of a $\sim 100 M_{\text{Jup}}$ primary (16A) and a $\sim 73 M_{\text{Jup}}$ (16B) secondary.

While young VLM datasets are dominated by small number statistics, they are suggestive of a moderately common ($6 \pm 3\%$) young ($< 10$ Myr) population of wide ($> 100$ AU), very low-mass ($M_{\text{tot}} < 0.2 M_\odot$), binary systems like Denis PJ161833.2 -251750.4, 2MASS J11011926-7732383, Oph#11 (Oph 1622-2405), and Oph#16 (Oph 1623-2402). Our estimate of the wide young binary fraction agrees well with the $5^{+6}_{-2}\%$ found in the Upper Sco by Bouy et al. (2006). We argue that, over time, the majority of these wide VLM systems become unbound leaving just the surviving (most tightly bound) fraction observable in the field today.

We suspect these wide systems likely become unbound since only $\sim 0.3 \pm 0.1\%$ of field VLM objects are wider than 100 AU today. Hence it appears that the field population is depleted in wide VLM binaries by a (selection effect corrected) factor of $X_{\text{evap}} = 15^{+20}_{-10}$. The exact mechanism for this evaporation of wide VLM systems is unlikely to be interactions with stars in the field or with molecular clouds and their sub-clumps. However, from the Fokker-Planck solutions of Weinberg et al. (1987), we find stellar encounters with “birth cluster stars” may be efficient in dissolving these wide binaries. Indeed such encounters may help boost the observed $sep$ past the $sep_{\text{catastrophic}} = 80 \left( \frac{M_{\text{tot}}}{0.1 M_\odot} \right)$ AU limit where catastrophic cluster encounters can occur. More detailed numerical studies will be required to better constrain the evolution of this evaporating population.

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Table 1. The Oph #11 Brown Dwarf Binary (Separation=1.943 ± 0.022"; PA=176.2 ± 0.5°)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>J</th>
<th>H</th>
<th>Ks</th>
<th>Ls</th>
<th>[3.6]</th>
<th>[4.5]</th>
<th>[5.8]</th>
<th>[8.0]</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆ mag</td>
<td>0.82 ± 0.03</td>
<td>0.69 ± 0.03</td>
<td>0.52 ± 0.03</td>
<td>0.36 ± 0.04</td>
<td>0.24 ± 0.04</td>
<td>0.11 ± 0.04</td>
<td>-0.20 ± 0.05</td>
<td>-0.51 ± 0.10</td>
</tr>
<tr>
<td>11A (mag)*</td>
<td>15.04 ± 0.05</td>
<td>14.19 ± 0.07</td>
<td>13.92 ± 0.07</td>
<td></td>
<td>13.24 ± 0.04</td>
<td>13.08 ± 0.03</td>
<td>12.96 ± 0.05</td>
<td>12.84 ± 0.11</td>
</tr>
<tr>
<td>11B (mag)*</td>
<td>15.86 ± 0.05</td>
<td>14.88 ± 0.05</td>
<td>14.44 ± 0.44</td>
<td></td>
<td>13.48 ± 0.04</td>
<td>13.19 ± 0.04</td>
<td>12.76 ± 0.05</td>
<td>12.34 ± 0.08</td>
</tr>
</tbody>
</table>

*a the J, H, and Ks fluxes are standard MKO magnitudes determined at the Gemini telescope. The Spitzer magnitudes at [3.6], [4.5], [5.8], and [8.0] μm are based on the standard Vega IRAC zeropoints of 276.79, 179.5, 116.69, and 63.122 Jy respectively. We determined new IRAC photometry with a proper binary PSF fit to the IRAC images. There may be an additional ∼15% absolute calibration uncertainty in the IRAC photometry (Evans et al. 2003).

Table 2. The Oph #16 VLM Binary (Separation=1.696 ± 0.005"; PA=218.29 ± 1.00°)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>J</th>
<th>H</th>
<th>Ks</th>
<th>Ls</th>
<th>[3.6]</th>
<th>[4.5]</th>
<th>[5.8]</th>
<th>[8.0]</th>
<th>[24] (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆ mag</td>
<td>0.691 ± 0.030</td>
<td>0.691 ± 0.022</td>
<td>0.757 ± 0.029</td>
<td>0.65 ± 0.03</td>
<td>0.67 ± 0.03</td>
<td>0.75 ± 0.04</td>
<td>0.75 ± 0.04</td>
<td>-a</td>
<td></td>
</tr>
<tr>
<td>16A (mag)b</td>
<td>11.19 ± 0.26</td>
<td>10.54 ± 0.17</td>
<td>10.20 ± 0.12</td>
<td>9.88 ± 0.03</td>
<td>9.60 ± 0.03</td>
<td>9.10 ± 0.03</td>
<td>8.12 ± 0.16</td>
<td>32 ± 5a</td>
<td></td>
</tr>
<tr>
<td>16B (mag)b</td>
<td>11.94 ± 0.26</td>
<td>11.23 ± 0.17</td>
<td>10.88 ± 0.12</td>
<td>10.53 ± 0.06</td>
<td>10.27 ± 0.05</td>
<td>9.85 ± 0.04</td>
<td>9.31 ± 0.10</td>
<td>16 ± 3a</td>
<td></td>
</tr>
</tbody>
</table>

*aΔ[24] was not determined, however, since 16B is consistently ∼0.75 mag fainter we have estimated that this ratio holds for the[24] μm mJy flux as well.

b Above magnitudes were dereddened by A_V = 3 ± 1 mag (similar to the A_V = 2 of Allers et al. 2006). The error in the extinction dominates the J, H, and Ks photometric errors. With the RV = 3.1 extinction law of Fitzpatrick (1999) we have dereddened our observed Oph 16A & B magnitudes by 0.78 mag at J, 0.51 at H and 0.36 at Ks for A_V = 3. Our integrated Oph 16 flux calibration is based on integrated flux values from the 2MASS point source catalog and the integrated IRAC values are from Allers et al. (2006).
Table 3. The Young, Wide, Low-Mass Ophiuchus Binaries (D=125 ± 25 pc)

<table>
<thead>
<tr>
<th>Allers #</th>
<th>2MASS Name</th>
<th>SpT</th>
<th>$T_{\text{eff}}$ (K)</th>
<th>Lum. log($L_\odot$)</th>
<th>Gravity$^a$ log(g) (Myr)</th>
<th>Age (Myr)</th>
<th>Mass (Jup)</th>
<th>Pro. Sep. (AU)</th>
<th>Period$^b$ (x10$^3$ yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11A</td>
<td>16222521-2405139</td>
<td>M9 ± 0.5</td>
<td>2375 ± 175</td>
<td>$-2.77 \pm 0.10$</td>
<td>4.25 ± 0.50</td>
<td>5 ± 2</td>
<td>17.5 ± 2.5$^c$</td>
<td>243 ± 55</td>
<td>20 ± 10</td>
</tr>
<tr>
<td>11B</td>
<td>–</td>
<td>M9.5 ± 0.5</td>
<td>2175 ± 175</td>
<td>$-2.96 \pm 0.10$</td>
<td>4.25 ± 0.50</td>
<td>–</td>
<td>15.5 ± 2.5$^c$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>16A</td>
<td>16233609-2402209</td>
<td>M5 ± 3$^d$</td>
<td>3000 ± 300</td>
<td>$-1.18 \pm 0.10$</td>
<td>–</td>
<td>~1</td>
<td>~100$^e$</td>
<td>212 ± 43</td>
<td>~8</td>
</tr>
<tr>
<td>16B</td>
<td>–</td>
<td>M5.5 ± 3$^d$</td>
<td>2925 ± 300</td>
<td>$-1.47 \pm 0.10$</td>
<td>–</td>
<td>–</td>
<td>~73$^e$</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

$^a$Surface gravities estimated based on the best synthetic spectra fits to our J and K spectra. However, a gravity of log(g) ~ 3.95 corresponds to the best fit of Oph#11A and Oph#11B to the spectral standards.

$^b$Periods estimated based on face-on circular orbits.

$^c$Masses of 11A and 11B determined from the full range of masses consistent with all of our determined range of gravities, ages, luminosities, and temperatures from the DUSTY tracks (Chabrier et al. 2000). No additional error due to unknown systematics in the models themselves have been added, hence these mass errors are likely underestimated.

$^d$Since no spectra have been obtained for 16A and 16B, these spectral types are simply estimated from our dereddened NIR colors from Table 2.

$^e$Masses of 16A and 16B estimated from the 1 Myr isochrone. Without a detailed spectroscopic observations it is impossible to be more accurate about the ages or masses of Oph 16 at this time.
Fig. 1.— Images of both binary systems found from our survey of Ophiuchus VLM objects. All images are in the Ks band. The Oph #11 image is seeing limited (FWHM=0.3") with the NIRI IR camera (0.02177"/pix) at the Gemini North Telescope. Whereas images of Oph #16 were obtained at the Keck II telescope with NIRC2 camera (0.010"/pix) and the LGS AO system. Locking on Oph #16 as its own tip-tilt star gave excellent \( FWHM = 0.05" \) LGS AO (Wizinowich et al 2006) corrected images. North is up and East left in all images.
Fig. 2.— Images of the Oph #11 system at J, H, & Ks (obtained in excellent FWHM $\sim 0.3''$ seeing at Ks) with the NIRI IR camera at the Gemini North Telescope. The Ls image is from the NIRC IR camera ($0.15''/\text{pix}^{-1}$) at the Keck I telescope. North is up, east to the left.
Fig. 3.— IRAC [3.6] micron (1.2″pix$^{-1}$) image of #11 (upper left; note north is 80° counterclockwise from up). In the lower left we show the residual (stretch intensified by 5 times for clarity) of the system fit to 1 PSF (clearly Oph #11 is not well fit by a single PSF). The second column from the left shows our #11 binary model ($Sep = 1.94″$, $PA = 176°$) with the best fit fluxes (in this case with a $\Delta[3.6]$ of 0.24 mag). The next (3$^{rd}$) column from the left shows a single star and its residual when fit with our IRAC PSF (giving a similarly good residual as our binary model). The upper image in the right-hand column shows a simulated system similar to the #11AB binary and then below it the residuals left after fitting a single PSF fit (note the similarity of this simulation to the comparable fit to the actual data shown in the left-hand column). The robustness of the binary fit gives confidence in our IRAC photometry to the $\sim$0.03-0.05 mag level. Similar fits were also obtained at [4.5], [5.8], and [8.0] μm for #11 and #16; see Tables 1 & 2 for the resulting mid-IR photometry.
Fig. 4.— The J-H, H-Ks color-color diagram for field (old) low-mass M, L, & T dwarfs. Note how the positions of 11A and 11B are similar to that of AB Pic b another very low-mass, young, object (Chauvin et al. 2005b). The offset in the positions of 11A and 11B from the dwarf locus is likely due to the low surface gravity of these objects compared to field dwarfs (Song et al. 2006). Figure adopted from Song et al. (2006).
Fig. 5.— The K-band NIRSPEC spectrum of Oph 11A (red line). Note the good agreement between the young L0 dwarf 2M0141 (from Kirkpatrick et al. 2006) and 11A. In particular, the good fit to the temperature sensitive CO lines suggests 11A is just slightly warmer than a young L0. The poorer fit of the gravity sensitive NaI and CaI to the older (30 Myr) star GSC8047 (from Chauvin et al. 2005a) suggests that 11A must be younger than 30 Myr (we have lowered the resolution of the Oph 11A spectra to match that of GSC8047).
Fig. 6.— Similar to Figure 5, except for 11B. Note the even better fit to 2M0141 for 11B. Hence we suggest that 11B is similar to a young M9.5 ± 0.5, consistent with the optical spectral type of M9.5-L0 found by Jayawardhana & Ivanov (2006b).
Fig. 7.— The J-band NIRSPEC spectrum of Oph 11A compared to a range of young brown dwarfs. Here we see the many gravity sensitive features in the J-band (McGovern et al. 2004) can be used to estimate the gravity (and hence age) of 11A. To minimize uncertainty we compare to other spectra obtained with the same instrumental set-up as we used. These J-band comparison spectra from the work of McGovern et al. (2004) and Kirkpatrick et al. (2006) show that 11A’s KI doublets and J-band pseudo-continuum best fit a brown dwarf of age 5 ± 2 Myr such as σ Ori 51 (McGovern et al. 2004). Moreover, the strength of 11A’s KI doublets (and poor fit to the pseudo-continuum) compared to the very young brown dwarf KPNO Tau-4 strongly suggests that the system age for Oph 11 is > 2 Myr.
Fig. 8.— Similar to Figure 7 but with 11B. We see the surface gravity of the 5 ± 2 Myr σ Ori 51 is the best fit. Moreover, the poor fit to KPNO Tau-4 strongly suggests that the system age for Oph 11 is > 2 Myr.
Fig. 9.— Comparison of our observed K-band spectra (red) to synthetic spectra (black) computed using up-to-date PHOENIX DUSTY atmosphere models (Hauschildt et al. in prep). See Section 3.3.1 for a discussion.
Fig. 10.— Same as Figure 9 except for the J-band instead of the K-band. See Section 3.3.2 for a discussion.
Fig. 11.— Synthetic 2MASS and IRAC fluxes for log(g)=3.95 and $T_{\text{eff}} = 2375$K and $T_{\text{eff}} = 2175$K. These SEDs were computed using up-to-date PHOENIX DUSTY atmosphere models (Hauschildt et al. in prep), assuming 125 pc as the distance to Oph #11. These SEDs demonstrate the significant IR excess for 11A (red points) and 11B (blue points) at $\lambda > 3\mu$m. Component 11B appears to have a much stronger excess than 11A. The integrated 24$\mu$m datapoint for the system is plotted since we could not resolve the system at 24$\mu$m. Overall, the strong warm dust excess and H$\alpha$ emission suggests ages $< 8$ Myr, consistent with our estimated $5 \pm 2$ Myr age.
Fig. 12.— An HR diagram where the dashed “vertical” lines are iso-mass contours for the DUSTY models (from left to right: 94, 73, 52, 42, 21, 16, 13, 10, & 7 M$_{\text{Jup}}$), while the four slightly more “horizontal”, lines are the DUSTY isochrones (top to bottom: 1 Myr (dash-dot) and 5 Myr (solid line), 10Myr (dash-dot) and 100 Myr (dash-dot)). The 2MASS 0535 data points (open circles) mark the only known low-mass, very young, binary with a well determined dynamical mass. The thick short diagonal lines representing the displacement from the measured luminosity and temperature to the values actually predicted by the DUSTY models. One can see that for the secondary of the 2MASS 0535 eclipsing binary system (in Orion; Stassun et al. 2006) the models have some error, but in general the binary is close to the relevant 1 Myr isochrone. Hence we can have some confidence in these models to estimate masses. From the intersection of the 11A (blue area) and 11B (red area) areas w.r.t. the estimated age of 3 – 7 Myr (from our NIR surface gravity measurements) we estimate masses of 13 – 21M$_{\text{Jup}}$ and 10 – 20M$_{\text{Jup}}$ for 11A and 11B. Therefore, the system appears to be a very low-mass brown dwarf binary.
Fig. 13.— DUSTY tracks of Chabrier et al. (2002) in terms of surface gravity (log(g) in cgs units) against temperature (T_{eff}). Hence, we can estimate masses independent of the possibly variable NIR luminosity of Oph 11. From our synthetic spectral fits (with the same models) we find log(g) > 3.75. Moreover, the existence of a strong IR excess and Hα emission (Jayawardhana & Ivanov (2006b)) suggests that the age of Oph 11 is < 8Myr. Therefore, we “shade-in” the remaining areas of model space that are self-consistent for 11A and 11B. For 11A (red “area”) we find 17^{+4}_{-5} M_{Jup} is the allowed mass range. For 11B (blue “area”) we find 14^{+3}_{-5} M_{Jup} is the allowed mass range.
Fig. 14.— Upper left a 1993.33 epoch red POSS II image of Oph 11A and Oph 11B (11B is brighter than 11A in this filter due to its stronger Hα emission). Note how nearby field PSF stars have circular PSFs very different from the Oph 11 system. This image shows the system with a separation of $2.05 \pm 0.20''$ and a $PA = 174 \pm 6^\circ$ which is consistent with the current (2006.55) orientation and separation of the binary. Hence, we measure only $\sim 3 \pm 5$ km/s of “motion” in the plane of the sky over the last 13.22 years, consistent with the system being a bound, common proper motion, pair. This image has been unsharp masked, and magnified 5x5. The bottom panels show the IR POSS II image of the Oph 16 system in 1982.66. We find in 1982.66 the system had a separation of $1.87 \pm 0.2''$ and $PA = 216.3 \pm 10^\circ$, this position is consistent with its current position 23.89 years later. This implies the Oph 16 system is likely also a bound common proper motion system. North is up and east is left in all images.
Fig. 15.— The Oph 11 system is compared to other known VLM and brown dwarf binaries (old VLM systems are open stars, open circles are young (< 10 Myr) VLM systems, and stellar mass binaries are solid symbols). Adopted from Close et al. (2003) and Burgasser et al. (2006).
Fig. 16.— Illustrating the uniquely low binding energy of the Oph #11 system compared to other known VLM systems. Note how our newly discovered Oph #16 binary is also weakly bound. Adopted from Close et al. (2003) and Burgasser et al. (2006).
Fig. 17.— Same as Fig. 15, but with the instability zones highlighted. The zones are determined by equations 1–4 which predict the maximum bound separations plotted as dashed “diagonal” lines from left to right as $sep_{\text{diffusive}^\ast}$, $sep_{\text{catastrophic}^\ast}$, $sep_{\text{diffusive}}$, and $sep_{\text{catastrophic}}$. Note how all young (< 10 Myr; open circles), wide, VLM systems are in the “Cluster Unstable” region. Therefore, we expect that many of these “cluster” ($n_* \sim 1000/pc^3$) binaries could be evaporated before joining the field (open stars > 100 AU). Hence, wide VLM binaries in the field should be rare—as observed. We suggest that only wide VLM systems in very low ($n_\ast \lesssim 100/pc^3$) density groups will survive and join the field.