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 BINARYSB

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ABSTRACT
We imaged five objects near the star-forming clouds of Ophichus with the Keck Laser Guide Star AO system. We resolved sources 11 (Oph 1622–2405) and 16 (Oph 1623–2402) from Allers and coworkers into binary systems. Source 11 is resolved into a 243 AU binary, the widest known for a very low mass (VLM) binary. The binary nature of source 11 was discovered first by Allers and independently here, during which we obtained the first spatially resolved R ~ 2000 near-infrared (J and K) spectra, mid-IR photometry, and orbital motion estimates. We estimate for 11A and 11B gravities (log g > 3.75), ages (5 ± 2 Myr), luminosities [log (L/L⊙) = −2.77 ± 0.10 and −2.96 ± 0.10], and temperatures (Teff = 2375 ± 175 K and 2175 ± 175 K). We find self-consistent DUSTY evolutionary model (Chabrier and coworkers) masses of 17.4 M⊙ and 14.6 M⊙ for 11A and 11B, respectively. Our masses are higher than those previously reported (13–15 M⊙ and 7–8 M⊙) by Jayawardhana & Ivanov. Hence, we find that the system is unlikely a “planetary mass binary,” as do Luhman and coworkers, 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 (≥100 AU), young (<10 Myr), roughly equal mass, VLM stellar and brown dwarf binaries. We deduce that ~6% ± 3% of young (<10 Myr) VLM objects are in such wide systems. However, only 0.3% ± 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: binaries: general — instrumentation: adaptive optics — stars: evolution — stars: formation — stars: individual (2MASS J16222521—2405139, 2MASS J16233609—240209) — stars: low-mass, brown dwarfs

1. INTRODUCTION
The system 2MASS 12073344–393254 (sep ~ 41 AU, 2MA12073344–393254) demonstrated that very low mass (VLM) objects could remain bound for at least 8 Myr (Chauvin et al. 2004, 2005a; Mamajek 2005; Song et al. 2006). A somewhat similar very wide (~241 AU), very young, nearly equal mass brown dwarf binary (2MASS J11011922–732328) has been discovered in Chameleon (Luhman 2004), while Billeres et al. (2005) discovered a wide (~200 AU), much older, field binary DENIS J0551–44. They noted that “wide ultracool binaries are undoubtedly rare in the field.” Indeed, of the ~69 field VLM binaries now known, only DENIS J0551–44 and DENIS 2200–30 (~38 AU) have separations wider than ~30 AU and total mass <0.2 M⊙ (Close et al. 2003; Bouy et al. 2003; see also Burgasser et al. 2007; Siegler et al. 2005 and references therein).

Calculations of opacity-limited fragmentation in a turbulent three-dimensional medium yield minimum masses ~7 Mj (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 [2006] was the first to resolve this system).

Allers et al. (2006) present a near-infrared (NIR; 1.2, 1.6, and 2.2 μm) imaging survey of several young star formation associations. By cross-correlation with the “Cores to Disks (c2d)” Spitzer [3.6], [4.5], [5.8], [8.0], and [24] μm legacy mid-IR survey (Evans et al. 2003) of these same star formation regions, they were able to identify 19 candidate very low, mass-objects, each of which appears to have a significant mid-IR excess in the Spitzer data set.

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

While Allers et al. (2006) estimate a mass of ~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 § 4.4.

We show, after an analysis of each component’s luminosity, surface gravity, age, and Teff, that the masses of 11A and 11B are likely just above the deuterium-burning limit (~13 Mj). 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 fourth lowest binding energy of any known VLM system.

In § 4.6 we note that Oph 11 and Oph 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 ≈15 times more common in very young clusters and associations. In § 4.6.3 we suggest that stellar encounters in these clusters have the potential to break up/evaporate these binaries.

2. OBSERVATIONS AND REDUCTIONS

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

We independently discovered the binary nature of the Oph 11 system with the Gemini NIRI camera (Hodapp et al. 2003) on 2006 July 1 (UT) in the J, H, and Ks bands (all other objects in our survey were observed with the Keck II LGS AO system). We then obtained Ls (~3.0 μm) images with the NICMOS camera on the Keck I telescope on 2006 July 7 (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 Oph 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 refer to this system as Oph 11 (and as Oph 1622–2405) since it was first mentioned in the widely available literature as source 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 sources 10, 11, 12, and 13 of Allers et al. (2006) would all also be "Oph 1622" due to their similar right ascension.

The night of 2006 July 1 (UT) was photometric, and zero points from photometric standards were used for calibration at J, H, and Ks. There are small (2MASS − Gemini = −0.12 ± 0.09, 0.16 ± 0.10, 0.06 ± 0.10 mag) differences between our calibration and the J, H, and Ks fluxes of source 11 in the Two Micron All Sky Survey (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] μm IRAC images of source 11. Utilizing a custom IRAC point-spread function (PSF) fitting program, we were able to detect (for the first time) both components of the binary in all IRAC passbands (see, e.g., Fig. 3). In all cases a double PSF model of a 1.94" binary with P.A. = 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 source 11 system components were obtained on 2006 August 9 with NIRSPEC in low-resolution mode on the Keck II telescope (McLean et al. 1998, 2000). We used a 0.57" × 42" slit and the image rotator to maintain the ~180° 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 ~ 2000. J-band observations utilized the NIRSPEC-3 order-sorting filter (1.143–1.375 μm), and K-band observations used the K filter (1.996–2.382 μm). For each filter a set of four frames was obtained in an ABBA nod pattern, nodding ~20" along the slit between the A and B positions. Integration times for each exposure were 360 s in the J band and 180 s in the K band. An A0 V calibrator star, HIP 80224, was observed in each band for a 60 s integration at each nod position and at a similar air mass 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,8 a package of IDL procedures developed specifically for the reduction

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8 See http://www2.keck.hawaii.edu/inst/nirspec/redspsc/.
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 911 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 (Paγ/C12 at 1.282/C22 μm in the J band and Brγ/C13 at 2.166/C22 μm 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 Teff 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 = 1500 for J band and R = 1900 for K band. The signal-to-noise ratio (S/N) is calculated from the maximum peak-to-peak variation and estimated to be S/N ≳ 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 and L dwarfs (see Fig. 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

![Fig. 2.—Images of the Oph 11 system at J, H, and Ks (obtained in excellent FWHM ~ 0.3″ seeing at Ks) with the NIRC IR camera at the Gemini North telescope. The Ls image is from the NIRI IR camera (0.15″ pixel−1) at the Keck I telescope. North is up, east to the left.](image)

### TABLE 1

| Parameter | J      | H     | Ks    | Ls  | [3.6] | [4.5] | [5.8] | [8.0] |
|-----------|--------|-------|-------|-----|-------|-------|-------|-------|
| Δmag      | 0.82 ± 0.03 | 0.69 ± 0.03 | 0.52 ± 0.03 | 0.36 ± 0.04 | 0.24 ± 0.04 | 0.11 ± 0.04 | −0.20 ± 0.05 | −0.51 ± 0.10 |
| 11A (mag) | 15.04 ± 0.05 | 14.19 ± 0.07 | 13.92 ± 0.07 | 13.24 ± 0.04 | 13.08 ± 0.03 | 12.96 ± 0.05 | 12.84 ± 0.11 |      |
| 11B (mag) | 15.86 ± 0.05 | 14.38 ± 0.05 | 14.44 ± 0.44 | 13.48 ± 0.04 | 13.19 ± 0.04 | 12.76 ± 0.05 | 12.34 ± 0.08 |      |

* 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 zero points 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).
highly (line of sight) extincted source since the visible spectrum of Oph 11 was measured to be that of a young M9 by Jayawardhana & Ivanov (2006a) and they (as do Allers et al. 2006, 2007) find that $A_V = 0$ 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 that the extinction toward 11A and 11B must be very low. Consistent with a low $A_V$, we note that there is little 24 μm IR cirrus in the immediate area around Oph 11. This is not surprising as Oph 11 is located ($D \sim 0.5$ ~1 pc) near the edge of the $^{13}$CO core of the ρ Oph cloud, although Oph 11 (and Oph 16) are still inside the ρ Oph survey area (and the $^{13}$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, e.g., Gorlova et al. 2003) we can measure $T_{\text{eff}}$ and spectral type for 11A and 11B. However, this first requires 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 to 2.5 μm by Kirkpatrick et al. (2006). They find that 2M0141 is best fitted by an L0 spectral type and by $T_{\text{eff}} = 2000 \pm 100$ 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 Figs. 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 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, Na i, Ca ii, and pseudocontinuum to the K-band spectrum of 2M0141 suggests a $T_{\text{eff}} = 2000$ K and ~5 Myr age (log $g = 4$).

When we compare 11B in the J-band to 2M0141 (middle trace of Fig. 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 ± 2 Myr), somewhat hotter (M9) brown dwarf 11 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 2300 K from the temperature scale of Martin et al. (1999), 2400 K from that of Luhman (1999), and 2400 K from Golimowski et al. (2004), we adopt a value of 2350 K for M9. So it appears that 11B could be as hot as $T_{\text{eff}} = 2350$ K from its J-band spectrum (but as cool as 2000 K in the K band). Therefore, we adopt $T_{\text{eff}} = 2175 \pm 175$ (M9.5 ± 0.5) as a reasonable match to the J- and K-band spectra of 11B compared to other young brown dwarfs. We note that 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 ~4.0 and age 5 ± 2 Myr. 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

### Table 2

| Parameter | $J$ | $H$ | $K_s$ | $[3.6]$ | $[4.5]$ | $[5.8]$ | $[8.0]$ |
|-----------|-----|-----|-------|--------|--------|--------|--------|
| $\Delta$mag | 0.691 ± 0.030 | 0.691 ± 0.022 | 0.757 ± 0.029 | 0.65 ± 0.03 | 0.67 ± 0.03 | 0.75 ± 0.04 | 0.75 ± 0.04 |
| 16A$^b$ (mag) | 11.19 ± 0.26 | 10.54 ± 0.17 | 10.20 ± 0.12 | 9.88 ± 0.03 | 9.60 ± 0.03 | 9.10 ± 0.03 | 8.12 ± 0.16 |
| 16B$^b$ (mag) | 11.94 ± 0.26 | 11.23 ± 0.17 | 10.88 ± 0.12 | 10.53 ± 0.06 | 10.27 ± 0.05 | 9.85 ± 0.04 | 9.31 ± 0.10 |

$^a$ The $\Delta$[24] was not determined; however, since 16B is consistently ~0.75 mag fainter, we have estimated that this ratio holds for the [24] μm 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 $K_s$ photometric errors. With the $R_V = 3.1$ extinction law of Fitzpatrick (1999) we have dereddened our observed Oph 16A and 16B magnitudes by 0.78 mag at $H$, and 0.36 mag at $K_s$ 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

| Allers Number | 2MASS System Name | Spectral Type | $T_{\text{eff}}$ (K) | Luminosity $\log L$ | Gravity $\log g$ | Age (Myr) | Mass ($M_J$) | Projected Separation (AU) | Period$^d$ ($\times10^3$ yr) |
|---------------|------------------|--------------|-----------------$\log L$ | $\log g$ | $\log g$ | ~1 | ~1 | ~73 | ... |
| 11A............| 16222521−2405139 | M9 ± 0.5 | 2375 ± 175 | −2.77 ± 0.10 | 4.25 ± 0.50 | 5 ± 2 | $T_{\text{eff}} = 424$ | 235 ± 55 | 20 ± 10 |
| 11B............| ... | M9.5 ± 0.5 | 2175 ± 103 | −2.96 ± 0.10 | 4.25 ± 0.50 | ... | ... | ... | ... |
| 16A............| 16233609−2402209 | M5 ± 3$^c$ | 3000 ± 300 | −1.18 ± 0.10 | ... | ... | ... | 212 ± 43 | 8 |
| 16B............| ... | M5.5 ± 3$^c$ | 2925 ± 300 | −1.47 ± 0.10 | ... | ... | ... | ... | ... |

$^a$ Surface gravities estimated based on the best synthetic spectra fits to our J and K spectra. However, a gravity of $\log g \sim 3.95$ 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 errors 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.

$^c$ Masses of 16A and 16B estimated from the 1 Myr isochrone. Without detailed spectroscopic observations it is impossible to be more accurate about the ages or masses of Oph 16 at this time.
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 K i doublets and its entire pseudocontinuum; McGovern et al. 2004); hence, we can reconcile the poor fit of 11B to KPNO Tau 4 and the good fit to /C27 Ori 51 by adopting an age of 5/C6 2 Myr (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 ~30 Myr are very unlikely since the strength of the Na i and Ca i lines in 11B (Figs. 5 and 6) is much weaker than that of GSC 8047 (a known 30 Myr old M9.5 Tuc association member; Chauvin et al. 2005c).

### 3.2.3. The Temperature and Age of 11A

We find that 11A is consistently ~200 K hotter than 11B from detailed spectral synthesis modeling of the J- and K-band spectra (§ 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 Figures 5 and 7. Hence, a Teff ~ 2375 ± 175 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.

Fig. 7.—J-band NIRSPEC spectrum of Oph 11A compared to a range of young brown dwarfs. Here we see that 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 setup 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 K i doublets and J-band pseudocontinuum 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 K i doublets (and poor fit to the pseudocontinuum) 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 Fig. 7, but for 11B. We see that 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 (P. H. Hauschildt et al. 2007, in preparation). See § 3.3.1 for a discussion.

3.3. Synthetic Spectral Fits

3.3.1. Temperatures

We consider how our adopted ~5 Myr age and M9 and M9.5 spectral type estimates compare to synthetic spectra with log g 3:95 (consistent with the DUSTY model’s 5 Myr isochrone) and T_eff = 2375 K for 11A and T_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 (P. H. Hauschildt et al. 2007, in preparation). The synthetic spectra do a reasonable job fitting Na i and Ca i, 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 overestimation of the temperatures from the synthetic CO lines was also seen in the similar case of 2M0141 (Kirkpatrick et al. 2006).

If we let T_eff and log g be free parameters, the very best fit to our observed spectra with the synthetic models suggests that ΔT_eff ~ 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 ΔT_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 that our adopted log g = 3.95 for Oph 11 is slightly too low for a good fit to the observed pseudocontinuum. A slightly better fit is obtained with log g = 4.25 ± 0.50. However, the adopted T_eff = 2375 and 2175 K for 11A and 11B combined with log g = 3.95 produce good agreement on the strength of the K i doublets. Hence, it appears that our adopted age of ~5 Myr (hence log g ~ 3.95) for 11A and 11B is reasonable.

In summary, the optimal synthetic fits suggest somewhat higher gravities (log g = 4.25 ± 0.50) but confirm our ΔT_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 Spectral Energy Distribution of 11A and 11B and Their Thermal IR Excess

Longward of 3 $\mu$m the spectral energy distribution (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) $H\alpha$ emission suggests that 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 about 16% ± 6% are estimated to be actively accreting (Bouy et al. 2007 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, VLM brown dwarf Cha 110913–773444, which also has an IR excess (Luhman et al. 2005). As noted in § 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 $K_s = 13.92 ± 0.05$ mag, a $K$-band bolometric correction of $-3.20 ± 0.15$ mag (Golimowski et al. 2004; appropriate for M9 ± 0.5), and noting that for an M9 star $K_s - K = 0.03$ mag (Daeomgen et al. 2007), we derive a photospheric luminosity for 11A of $L/L_\odot = -2.77 ± 0.10$. This luminosity excludes any contribution from the excess IR emission. Similarly, we find (with $B_{K} = -3.10 ± 0.15$ mag for an M9.5 ± 0.5) that $\log (L/L_\odot) = -2.96 ± 0.10$ 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 H-R 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 13–21 M$_J$ and 10–20 M$_J$ 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. In addition, the range of NIR photometry from Allers et al. (2006), Jayawardhana & Ivanov (2006b), 2MASS, and our work suggests that 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 $\Delta K_s$ values are close to those 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 $K_s$ flux is just 6% brighter than the 2MASS value, whereas Jayawardhana & Ivanov (2006b) find values ∼30% brighter. Their significantly brighter $K_s$ 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). On the other hand, Allers (2006) and Allers et al. (2006) find $K_s = 14.03$ mag for 11B, some 40% brighter than we do in this study. Hence, deriving masses primarily based on NIR luminosity for source 11 may be problematic for two reasons: first, there may be a significant underestimation of mass when one uses $J$ and $H$ fluxes and the DUSTY models (Close et al. 2005, 2007); second, source 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 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 is <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 >2 Myr (witness the very poor fit of KPNO Tau 4). 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 that masses of $17^{+4}_{-5}$ $M_J$ and $14^{+3}_{-5}$ $M_J$ 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 H-R diagram masses of 13–21 $M_J$ and 10–20 $M_J$ for 11A and 11B. Hence, our final adopted masses are $17^{+4}_{-3}$ $M_J$ and $14^{+3}_{-3}$ $M_J$. 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 $M_J$ deuterium limit and above the 14–15 $M_J$ and 7–8 $M_J$ masses found by Jayawardhana & Ivanov (2006b).

Hence, we also estimate a luminosity (and distance) independent mass based on our log $g$ and age estimates in the next section.

### 4. DISCUSSION

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

Ophiuchus 11B possesses a strong mid-IR (5 and 8 $\mu$m) excess, and 11A a weaker one (see Fig. 11). Mid-IR excesses are common only among stars younger than <8 Myr (Mamajek et al. 2004; Silverstone et al. 2006; Rhee et al. 2007 and references therein). The strong H$_\alpha$ emission measured by Jayawardhana & Ivanov (2006b) for 11A and 11B suggests that source 11 is actively accreting and associated with the molecular cloud. Indeed, Wilking et al. (2005) find active accreters (classical T Tauri stars) ranging in age from 0.3 to 10 Myr in the 1 pc area around the Oph cloud (including the location of Oph 11 and Oph 16). Our derived $5^{+2}_{-2}$ Myr age of source 11 is consistent with Oph 11’s $\sim$0.5” ($\sim$1 pc) distance from the $\rho$ 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 ($A_V \sim 0$ mag) to Oph 11 (despite being in the line of sight to the $^{13}$CO cloud), we suggest that Oph 11 is at a distance of $\sim$125 $\pm$ 25 pc. In other words, Oph 11 is likely slightly in front of the $\sim$150 pc “halo” of $\sim$3 Myr objects around the $\rho$ Ophi cloud core, which typically have $A_V > 1$ mag.
13.22 yr is only 11A and 11B appear in the RG610 POSS II "red" filter images. Hence, 11A and 11B very likely form a binary separation is 2
Ivanov 2006b). In the 1993.33 epoch red POSS II images the is seen in the POSS II "blue" (GG395 filter). However, both tect in the POSS II "IR" (RG715) images; only a very faint The very red optical colors of 11B make it impossible to de-
ing (due to 11A being a relatively fast moving foreground object). We can use archival POSS II images to determine if the pair's orientation on the sky is chang-
tically its observed proper motion is smaller than the expected

Fig. 13.—DUSTY tracks of Chabrier et al. (2000) 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 <8 Myr. Therefore, we “shade in” the remaining areas of model space that are self-consistent for 11A and 11B. For 11A (red region) we find that 17\(\frac{1}{2}\) M J is the allowed mass range. For 11B (blue region) we find that 14\(\frac{1}{2}\) M J is the allowed mass range.

(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\(\pm\)0.20 at P.A. = 174° \pm 6°, which may be compared to our images (Figs. 1 and 2; sep = 1.943\(\pm\)0.022\(\), P.A. = 176.2° \pm 0.5\(\). The system will become unbound in the future (see § 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 ± 1 and M8 ± 1 for 11A and 11B (from the low-resolution R ∼ 300 NIR spectra of Allers 2006). They derived ages of ∼20 Myr and masses of 65 and 35 M J from DUSTY models. A more recent work by the same group (Luhman et al. 2007) finds types of M7.25 and M8.75 and masses ∼59 and ∼21 M J for 11A and 11B, and like us, they derive an age of ∼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 ∼5 Myr ages. Hence, both of these studies use/compose templates of somewhat younger (∼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 eff.

Very recently Brandeker et al. (2006a) 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, respectively, 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. (2006a) find masses of 13\(\frac{1}{2}\) M J and 10\(\frac{1}{4}\) M J for 11A and 11B, respectively (slightly lower, yet consistent, with our 17\(\frac{1}{2}\) M J and 14\(\frac{1}{2}\) M J masses).

In summary, 11A is likely above the deuterium-burning limit (∼13 M J), 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 ∼58–13 M J). In the case of 11B there is better agreement (M8.75–M9.5, and masses of 21–10 M J). All recent studies agree that Oph 11AB is best described as a young (∼5 Myr), very wide (∼240 AU), low-mass (M tot ∼ 23–80 M J) brown dwarf

4.3. Are 11A and 11B Physically Bound?

Comparison of the epoch 1993.33 and current images shows that the differential displacement of 11A and 11B over the last 13.22 yr is only ∼3 ± 5 km s\(^{-1}\), consistent with expectations for a physical system this wide [estimated period (2 ± 1) \times 10^4 yr; Table 3]. However, since all members of the Ophiuchus asso-

ication 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 arcmin\(^2\) they found two ∼M8–M9 objects (sources 11 and 12). Follow-up optical spectra by Jayawardhana & Ivanov (2006a) showed that (in the optical) source 12 appears to be a background quasar. We in fact find source 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.

However, our observations. Hence, one would expect in Ophiuchus to find one late M/early L object in every 1700 arcmin\(^2\). Therefore, the odds of a chance alignment of such two 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\(^{-1}\) escape velocity of the system, then the current 237 AU projected separation suggests that they must have been bound until just ∼2 \times 10^{-5} 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 § 4.6.3).
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’s object 16 into two components at JHKs (Fig. 1 and 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 source 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, source 16 is just 0.3° (~0.6 pc) 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, then we need an extinction of A_V ~ 3 ± 1 to have these objects fall near the 1 Myr isochrone of ρ 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 toward source 16, we find (see Table 2) for 16A J – K = 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 Te = 3000 ± 300 K, and for 16B Te = 2925 ± 300 K (Golimowski et al. 2004). In the same manner as source 11, we find (with BC_K = −2.95) log (L/L_⊙) = −1.18 ± 0.10 for 16A and log (L/L_⊙) = −1.47 ± 0.10 for 16B (where BC_K = −3.00; Golimowski et al. 2004). The luminosity errors of source 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 H-R 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 Fig. 12) we estimate masses of \(~100\,M_J\) for 16A (likely a VLM star) and \(~72\,M_J\) for 16B (likely a high-mass brown dwarf or VLM star). Allers et al. (2006) estimated a mass for Oph 16AB of \(~110\,M_J\). 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 suggest 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 (sep \(=1.696''\pm 0.005''\), P.A. = 218.29° ± 1.00°; Fig. 1) is consistent with its orientation in 1982.66 (sep \(=1.877''\pm 0.2''\), P.A. = 216° ± 10°; Fig. 14). This is exactly what we would expect for a system with a very long period of \(~8 \times 10^5\) yr (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) that such a hypothetical foreground system would have a photometric distance of \(~10\) pc to match 16A’s brightness and very red (underreddened) magnitudes \((K_s = 10.56\) and \(J-K_s = 1.41\)). Such a VLM binary would have a period of \(~170\) yr, and so in the 23.89 yr between Figures 1 and 14 one would expect \(~50\)° of rotation. However, over the last 23.89 yr the system has only changed by a \(\Delta P.A. = 1.9°\) \(\pm 10.0°\), 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 are less than \(~10^{-5}\). Hence, we conclude that Oph 16AB is a newly discovered, wide (\(~212\) AU), VLM \((M_{tot} \sim 0.17\,M_\odot)\) binary system in the Ophiuchus cloud complex.

4.6. Oph 11 and Oph 16 Compared with Other VLM Binaries

Figures 15 and 16 show how Oph 11 and Oph 16 compare with other known binary systems. Oph 11 is the second least massive binary known (with \(M_{tot} \sim 0.031\,M_\odot\), 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 Figs. 15 and 16). Hence, one might predict that systems like Oph 11 will tend to become unbound as they age.

Fig. 15.—Oph 11 system compared to other known VLM and brown dwarf binaries (old VLM systems are open stars, young \(<10\) Myr VLM systems are open circles, and stellar mass binaries are filled symbols). Adopted from Close et al. (2003) and Burgasser et al. (2007).

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. (2007).

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 objects (not counting source 12) of the Allers et al. (2006) Oph sample (their sources 8, 10, and 16) and the two M8 objects (GY 264 and GY 3) of Wilking et al. (2005) with Keck II LGS AO and found that sources 11 (with NIR1) and 16 (\(\sim\)33\%\ ± 23\%\ of the sample) were binaries, and 100\% of our binaries were wide.\footnote{Very recently, Artigau et al. (2007) detected a possible \(~5\)100 AU VLM system which might be \(~30\) Myr old.}

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 members of the Allers et al. (2006) Ophiuchus sample are young, wide, VLM binaries. Moreover, Bouy et al. (2006a) 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, DENISP J161833.2-251750.4AB, is spectroscopically confirmed (Luhman 2005), and another, USCO 1600AB, is likely also bound (Bouy et al. 2006a). In contrast, Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) surveys of Upper Sco (5 Myr; Kraus et al. 2005) found no young wide VLM binaries. Bouy et al. (2006a) estimate (including the nondetection of Kraus et al. 2005) that \(~25\%\) (3/12) of VLM binaries in Upper Sco are wide. In summary, Bouy et al. (2006a) find two solid, wide (>100 AU), VLM binaries out of 40 VLM objects; hence, \(f_{VLM\text{wide, young}} \sim 5\%\) in the Upper Sco OB association.

The \((\geq\) 4 AU) spatial resolution survey of the lower density Taurus association of Kraus et al. (2006) with HST ACS found that 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, \(f_{VLM\text{wide, young}} \sim 7\%\) \pm 5\% in Taurus and Ophiuchus. This is very consistent with the \(~5\%\) found in the Upper Sco cluster. Merging all the surveys indicates that 4/68 young (<10 Myr) VLM objects that were observed at high resolution (sep \(\geq\) 5 AU) were found to be wide (>100 AU) binaries. Therefore, we adopt \(f_{VLM\text{wide, young}} \sim 6\%\ \pm 3\%\). 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 (\(f_{\text{VLM wide}}\)) 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 \(X_{\text{evap}} = f_{\text{VLM wide, old}}/f_{\text{VLM wide, old}}\) as the fraction of wide VLM binaries that have "evaporated" as these binaries age.

Of the 69 field (old; 0.5–10 Gyr) VLM (\(M_{\text{tot}} < 0.2 \, M_\odot\)) binaries currently known (VLM Binary Archive), only DENIS 0551 is wider than 100 AU. Hence, only \(\sim 1.4\%\) 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. 2007 and references within) have all failed to find a single wide (>50 AU) VLM field binary despite being sensitive to \(\text{sep} \geq 2\) AU and masses \(\geq 13\, M_j\). The 132 VLM (M7–L8) study of Allen et al. (2007) alone suggests that the frequency of wide VLM systems must be \(f_{\text{VLM wide, old}} < 2.3\%\) in the field at the 95% confidence level.

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) and Siegler et al. (2005) 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 IRSF, and Allen et al. (2007) have 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 \(f_{\text{VLM wide, old}} < 1/265 = 0.37\%\). The lower limit to frequency can be bounded by the fact that one wide system exists; hence, of the 580 L and T field dwarfs known (Dwarf Archives), only 1 is a wide binary, so \(f_{\text{VLM wide, old}} > 1/580 = 0.17\%\). Hence, we adopt \(f_{\text{VLM wide, old}} \sim 0.3\% \pm 0.1\%\). This is much smaller than our young wide VLM frequency of 6\% \pm 3\%.

A more careful analysis of the problem is warranted, it is still clear that the frequency of wide (>100 AU) VLM binaries (\(M_{\text{tot}} < 0.2 \, M_\odot\)) is \(\sim 20\%\) times higher for young (<10 Myr) VLM objects than for old field VLM objects.

A small observational selection effect is that a much older (~5 Gyr) analog of Oph 11B may be 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 2MASS 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 binary of 3/68 = 4.4\% \pm 2.5\% and hence a corrected \(X_{\text{evap}} = 15^\%\). 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 (~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 \(V_{\text{rel}} \sim 1\, \text{km s}^{-1}\) 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. 1987), 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 \(10^3–10^4\) 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 (<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 the Weinberg et al. (1987) analytic solution of Fokker-Planck (FP) coefficients describing advective diffusion of a binary due to stellar encounters is \(t_{\text{evap}} \sim 3.6 \times 10^2(n_{\text{rel}}/0.05\, \text{pc}^{-3})^{-1}(M_{\text{tot}}/M_\odot)^2(M_2/M_\odot)^2(V_{\text{rel}}/20\, \text{km s}^{-1})/(a_0/\text{AU})^{-1}\) Gyr, where \(t_{\text{evap}}\) is the time required to evaporate a binary of an initial semimajor axis of \(a_0\), and the number density of stellar perturbers is \(n_{\text{rel}}\), of mass \(M_2\) and relative velocity \(V_{\text{rel}}\) (adopted from Weinberg et al. [1987], assuming, as they do, that their In \(\Lambda \sim 1\)). Hence, the maximum projected separation of a bound binary (assuming semimajor axis \(a = 1.26 \times \text{yr}^{-1}\), Fischer & Marcy 1992) to survive 10 Gyr in the field is given by

\[
\text{sep}_{\text{diffusive}} = 28 \times 10^3 \left(\frac{0.16}{0.05\, \text{pc}^{-3}}\right)^{-1} \left(\frac{M_{\text{tot}}}{M_\odot}\right) \left(\frac{0.7}{M_\odot}\right)^2 \text{AU},
\]

\[
\sim 1800 \left(\frac{M_{\text{tot}}}{0.1\, M_\odot}\right) \text{AU},
\]

where we have used the measured Galactic disk mass density of \(0.1\, M_\odot\, \text{pc}^{-3}\), an average perturber mass of \(0.7\, M_\odot\), and \(V_{\text{rel}} \sim 20\, \text{km s}^{-1}\) (Pham 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. (1987) we find that the maximum projected separation (sep) of a binary to stay bound with respect to close encounters over 10 Gyr in the field is

\[
\text{sep}_{\text{catastrophic}} = 52 \times 10^3 \left(\frac{0.16}{0.05\, \text{pc}^{-3}}\right)^{-1} \left(\frac{M_{\text{tot}}}{M_\odot}\right) \left(\frac{0.7}{M_\odot}\right)^2 \text{AU},
\]

\[
\sim 3300 \left(\frac{M_{\text{tot}}}{0.1\, M_\odot}\right) \text{AU}.
\]

It is clear that all field VLM binaries with \(M_{\text{tot}} \geq 0.1\, M_\odot\) will be stable against any type of stellar encounter as long as \(\text{sep} \leq 1800\) 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 Figure 17 all the VLM binaries are not in the "field unstable" region (since \(\text{sep} < \text{sep}_{\text{diffusive}} < \text{sep}_{\text{catastrophic}}\)). 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 (filled triangles in Fig. 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 \(X_{\text{evap}}\) is \(\sim 15^\%\). Besides being young, all the known wide VLM systems are in the Chamaeleon I (2M1101) or Ophiuchus/Upper Sco/Sco-Cen OB...
in the field. encounters have much longer interaction timescales (since have much higher densities than the field. It is also true that the clusters; Gutermuth et al. 2005). These clusters (or associations) for these “clusters” (in general agreement with other similar-sized (Wilking et al. 2005). In summary, we adopt a mean 

\[
\text{core of Chamaeleon I, with} \quad \text{clusters. Since 2M1101 is near the lower core of Chamaeleon I, with } \sim 100 \text{ members with a core radius of } \sim 0.25 \text{ pc (Luhman 2004), we estimate that near 2M1101 } n_\star \sim 1500 \text{ pc}^{-3}. \text{For the Ophiuchus core there are } >200 \text{ members within a radius of } \sim 0.3 \text{ pc (Wilking et al. 2005) and so } n_\star \sim 1800 \text{ pc}^{-3}. \text{At the distance of Oph 11 and Oph 16 there are } \sim 100 \text{ members, but the density drops to } n_\star \sim 50–220 \text{ pc}^{-3} \quad (\text{Wilking et al. 2005). In summary, we adopt a mean } n_\star \sim 1000 \text{ pc}^{-3} \text{ for these “clusters” (in general agreement with other similar-sized clusters; Gutermuth et al. 2005). These clusters (or associations) have much higher densities than the field. It is also true that the encounters have much longer interaction timescales (since } V_{\text{rel}} \lesssim 3 \text{ km s}^{-1}; \text{ 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 \text{ Myr of the mean cluster density, then from the above equations we have}

\[
\text{sep}_{\text{cluster}}^{\text{diffusive}} \sim 28 \times 10^3 \left( \frac{1000}{0.05 \text{ pc}^{-3}} \right)^{-1} \left( \frac{M_{\odot}}{M_{\star}} \right) \times \left( \frac{0.7}{M_{\odot}} \right)^{-2} \left( \frac{3}{20 \text{ km s}^{-1}} \right) \sim 44 \left( \frac{M_{\odot}}{0.1 M_{\odot}} \right) \text{ AU.} \quad (3)
\]

In the case of a catastrophic encounter we have

\[
\text{sep}_{\text{cluster}}^{\text{catastrophic}} \sim 52 \times 10^3 \left( \frac{1000}{0.05 \text{ pc}^{-3}} \right)^{-1} \left( \frac{M_{\odot}}{M_{\star}} \right) \times \left( \frac{0.7}{M_{\odot}} \right)^{-2} \left( \frac{3}{20 \text{ km s}^{-1}} \right) \sim 80 \left( \frac{M_{\odot}}{0.1 M_{\odot}} \right) \text{ AU.} \quad (4)
\]

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{cluster}}^{\text{diffusive}} \leq \text{sep} \leq \text{sep}_{\text{cluster}}^{\text{catastrophic}}. \text{ 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 (noncatastrophic) 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. (2006b) implies that an M_{\odot} < 0.1 M_{\odot} binary is “soft” if \(a > 64 \text{ 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 eq. [4]), yet their solutions still predict that Oph 11 would become unbound in } \sim 11 \text{ Myr similar to our expectations above.}

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

Our scenario does predict that once the system’s birth clusters themselves dissolve, } F_{\text{VLM wide}} \sim F_{\text{VLM wide old}}. \text{ 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\% \text{ + 0.1\%. 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\% \text{ + 0.1\%. The ideal cluster for such a search would be the Pleiades (age } \sim 120 \text{ Myr, } D \sim 120 \text{ pc). Several large } \text{HST} \text{ and AO surveys have failed to

*Fig. 17.* Same as Fig. 15, but with the instability zones highlighted. The zones are determined by eqs. (1)–(4), which predict the maximum bound separations plotted as dashed “diagonal” lines from left to right as sep_{\text{cluster}}^{\text{diffusive}}, sep_{\text{cluster}}^{\text{catastrophic}}, sep_{\text{field}}^{\text{diffusive}}, \text{ and sep}_{\text{field}}^{\text{catastrophic}}. \text{ 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_\star \sim 1000 \text{ pc}^{-3}) \text{ binaries could be evaporated before joining the field (open stars). Hence, wide VLM binaries in the field should be rare, as observed. We suggest that only wide VLM systems in very low (} n_\star \lesssim 100 \text{ pc}^{-3}) \text{ density groups will survive and join the field.}
detect a single wide VLM binary in this cluster (Martin et al. 2003; Bouy et al. 2006b). A similar lack of wide systems has been found in the older Hyades (Siegler et al. 2003). Thus, by \(\sim 100\) Myr there is some evidence that the wide binary population has mainly been evaporated, as Figure 17 and equations (3) and (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 \(a_{\rm crit} \sim 1 \times 10^8\) AU, which is too wide to affect \(\sim 200\) 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 subclumps (Weinberg et al. 1987), but they are not relevant in the VLM regime.

5. CONCLUSIONS

We have obtained the first spatially resolved \(R \sim 2000\) NIR (\(J\) and \(K\)) 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 \((T_\text{eff} = 2375 \pm 175\) K and \(2175 \pm 175\) K). We find self-consistent DUSTY evolutionary model (Chabrier et al. 2000) masses of \(17\,\pm\,2\,M_J\) and \(14\,\pm\,5\,M_J\) for 11A and 11B, respectively. Our masses are higher than the previously reported 13–15\(M_J\) and 7–8\(M_J\) masses of Jayawardhana & Ivanov (2006b). Hence, we find that the system is unexpectedly a planetary mass binary, but it has the second lowest mass and lowest binding energy of any known binary.

The Oph 16 binary (Oph 1623–2402) is also an unusually wide (projected separation of 212 AU), VLM binary composed of a \(\sim 100\,M_J\) primary (16A) and a \(\sim 73\,M_J\) (16B) secondary.

While young VLM data sets are dominated by small number statistics, they are suggestive of a moderately common \((\sim 6\%)\) binary fraction \((\sim 100\,M_J)\), but they are not relevant in the VLM regime.

We suspect that these wide systems likely become unbound since only \(\sim 0.3\%\) of \(1\) 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 subclumps. However, from the FP solutions of Weinberg et al. (1987), we find that stellar encounters with “birth cluster stars” may be efficient in dissolving these wide binaries. Indeed, such encounters may help boost the observed separation past the \(X_{\text{evap}} = 15^{+20}_{-10}\) 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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