NEW PHOTOMETRY AND SPECTRA OF AB DORADUS C: AN ACCURATE MASS DETERMINATION OF A YOUNG LOW-MASS OBJECT WITH THEORETICAL EVOLUTIONARY TRACKS

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ABSTRACT

We present new photometric and spectroscopic measurements for the unique, young, low-mass evolutionary track calibrator AB Dor C. While the new Ks photometry is similar to that we have previously published, the spectral type is found to be much earlier. Based on new H and K IFS spectra of AB Dor C from Thatte et al. (Paper I), we adopt a spectral type of M5.5 ± 1.0 for AB Dor C. This is considerably earlier than the M8 ± 1 previously estimated by Close et al. and Nielsen et al. yet is consistent with the M6 ± 1 independently derived by Luhman & Potter. However, the spectrum presented in Paper I and analyzed here is a significant improvement over any previous spectrum of AB Dor C. We also present new astrometry for the system, which further supports a 0.090 ± 0.005 $M_\odot$ mass for the system. Once armed with an accurate spectrum and $K_s$ flux, we find $L = 0.0021 ± 0.0005 \, L_\odot$ and $T_{\text{eff}} = 2925^{+170}_{-145} \, \text{K}$ for AB Dor C. These values are consistent with a $\sim 75 \, \text{Myr}$, 0.090 ± 0.005 $M_\odot$ object like AB Dor C according to the DUSTY evolutionary tracks. Hence, masses can be estimated from the H-R diagram with the DUSTY tracks for young low-mass objects such as AB Dor C. However, we cautiously note that underestimates of the mass from the tracks can occur if one lacks a proper (continuum-preserved) spectrum or is relying on near-infrared fluxes alone.

Subject headings: binaries: general — instrumentation: adaptive optics — stars: evolution — stars: formation — stars: individual (AB Doradus C) — stars: low-mass, brown dwarfs

1. INTRODUCTION

There is currently great interest in the direct detection of extrasolar planets, brown dwarfs, and very low mass stars. The study of such young, low-mass objects has been yielding increasingly fruitful science, yet the field remains dependent on evolutionary models to properly interpret the data that are collected from these objects. In particular, mass, while a fundamental property, is very rarely measured directly (through orbital dynamics) and instead must be inferred from theoretical tracks (e.g., Burrows et al. 2003; Chabrier et al. 2000). It is thus of great interest to discover calibrating objects that can link a dynamically measured mass with observables such as accurate near-infrared (NIR; 1–2.5 μm) fluxes and spectral types.

AB Doradus A was suspected of having a low-mass companion because of VLBI and Hipparcos measurements of an astrometric wobble (Guirado et al. 1997). Recently, Close et al. (2005) reported the first direct detection of this low-mass companion (AB Dor C) to the young star AB Dor A, along with the first measurements of the $JHK_s$ fluxes, spectral type, and dynamically determined mass of AB Dor C. Upon comparing these results with the predictions of Chabrier et al. (2000), the models were found to be systematically overpredicting the fluxes and temperature of AB Dor C (especially at $J$ and $H$), given a system age of 50 Myr. Put another way, the model masses seem to be underestimating the mass of a low-mass object given its age, and $J$ and $H$ NIR fluxes, and spectral type. Since the publication of these results, another calibrating object has been reported by Reiners et al. (2005): UScoCTIO 5. While this equal-mass binary is younger ($\sim 8$ Myr) and more massive (total mass $\geq 0.64 \, M_\odot$) than AB Dor C, Reiners et al. found the same trend of models’ underpredicting masses based simply on photometric and spectroscopic data applied to the Hertzsprung-Russell (H-R) diagram. A similar trend for such masses was previously noted by Hillenbrand & White (2004). Moreover, this trend has been theoretically predicted for higher masses by Mohanty et al. (2004), and by Marley et al. (2005) for planetary masses. Hence, it is critically important to accurately calibrate the evolutionary tracks to determine if there are systematic errors. In particular, obtaining an accurate $T_{\text{eff}}$ from spectra of low-mass, young objects is challenging and makes comparison with evolutionary tracks difficult (Chabrier et al. 2005).

Recently, Nielsen et al. (2005) obtained new orbital epochs and confirmed the previous mass of AB Dor C of 0.090 ± 0.005 $M_\odot$, with the technique of Guirado et al. (2006). Hence, AB Dor C has a uniquely well known dynamical mass for a young ($\sim 75$ Myr) low-mass object. Only Gl 569Bab has a similarly well determined mass, but it is thought to be somewhat older ($\sim 300$ Myr; Zapatero Osorio et al. 2005), although a younger age ($\sim 100$ Myr) and binnar of Gl 569Bab have recently been proposed (Simon et al. 2006). Also, the lack of lithium in the spectrum of Gl 569B (Zapatero Osorio et al. 2005) is surprising. Hence, there is a need to quantify the AB Dor A/C system as closely as possible, to have an additional calibrator for evolutionary models of young, low-mass objects.

The age of AB Dor (and its associated moving group) is also somewhat uncertain; Luhman et al. (2005) argue for an older age of the AB Dor group of 75–150 Myr, while Nielsen et al. (2005) find 75 ± 25 Myr. Recently, López-Santiago et al. (2006) argued for a 50 Myr age for the core of the AB Dor moving group (which includes AB Dor A), as did Zuckermand et al. (2004) in the original “AB Dor moving group” paper. Recently, Janson et al. (2007) found an age range of 50–100 Myr. Here we adopt an “average” age of 75 Myr for the system.

There is also uncertainty in the spectral type of AB Dor C. The small separation between components A and C of only 0.155",
combined with the contrast of over 100, made an accurate spectral type difficult to measure in the data set of Close et al. (2005). A reanalysis of the Close et al. spectra by Nielsen et al. (2005) suggested a spectral type of M8 \pm 1. However, an independent reanalysis of the data by Luhman & Potter (2005) suggested a spectral type of M6 \pm 1. The importance of this temperature is paramount to plotting AB Dor C on the H-R diagram to calibrate the accuracy of the evolutionary tracks. These past papers high-light the difficulty in trying to determine the spectral type of a faint companion within 0.16" of a bright star with a long-slit spectrograph fed by adaptive optics (AO). Indeed, none of these past reductions of the AO long-slit spectra were able to preserve the continuum of AB Dor C. Hence, the true spectrum of C could not be accurately determined.

In a companion to this paper (Thatte et al. 2007, hereafter Paper I), we report on new, excellent integral field spectroscopy (IFS) of AB Dor A and C, observed with the SINFONI instrument at the Very Large Telescope. Using the new data analysis technique of point-spread function (PSF) scaling and differencing (PSD), we were able to effectively eliminate all contamination from AB Dor A, to produce a spectrum of AB Dor C with very high signal-to-noise ratio (S/N), which also preserves the continuum. The PSD technique is able to achieve very high contrast (\sim 9 mag at 0.2") without a coronagraph, and without any prior assumptions about the spectral characteristics of the companion object.

In this paper, we present new VLT Science Archive $K_s$ photometry and astrometry for AB Dor C and a more accurate $H$ and $K$ spectrum and a new temperature of AB Dor C. Then we compare the accuracy of the mass of AB Dor C predicted by the popular DUSTY theoretical tracks (Chabrier et al. 2000).

2. OBSERVATIONS AND REDUCTIONS

The AB Dor system (A, C, and their companion Ba/Bb, 8.87" distant) was observed with the VLT NACO AO system (Lenzen et al. 2003; Rousset et al. 2003) on 2005 January 7 by R. Neuhauser and coworkers in the $K_s$ band. We have reduced these archive data with our NIR AO data reduction IRAF pipeline (Close et al. 2002, 2003).

The $K_s$ images were fully flat-fielded, sky- and dark-subtracted, cleaned of bad pixels, and aligned and medianed (see Close et al. 2003 for more details about our AO pipeline). Only the first 18 of the 200 x 347 s $K_s$ images were reduced, since the seeing became worse after these first 18 images. We also observed AB Dor A and C with the SINFONI IFS, as described in Paper I, which provides extensive details of the IFS observations and reductions.

3. ANALYSIS

3.1. The $K_s$ Flux and Astrometry of AB Dor C

To accurately measure the flux of a tight, faint companion is never trivial. However, by 2005 January AB Dor C had moved out to a 0.22" separation from AB Dor A. While this may seem a very small separation, it is considerably better than the 0.155" separation during the 2004 February discovery images of Close et al. (2005). Hence, we should be able to better gauge the flux of AB Dor C at this later epoch.

To measure the brightness of AB Dor C, we utilized an unsaturated PSF image (in the narrowband 2.12 \mu m filter) of AB Dor A that was taken just before the AB Dor $K_s$ data set. This 2.12 \mu m "PSF" image was taken at the same air mass and seeing as the $K_s$ images. Also, the exposure times were the same (integration time 0.347 s, 200 co-adds) for the PSF and $K_s$ images. The FWHM of the PSF appeared similar to that of AB Dor C, so we have some confidence that this was a good PSF.

We shifted (with a cubic spline) and scaled this PSF image until subtracting it led to the complete removal of the flux from C from the reduced $K_s$ images. However, as is clear from Figure 1, there is some residual flux or "superspeckles" surrounding C's position, due to component A. Therefore, it is impossible to absolutely determine the flux of C, as a consequence of some uncertainty in A's PSF. We adopt the mean flux of AB Dor C as that where the residual flux of A at the position of C is equal to that 180° on the other side of A's PSF (see Fig. 1, bottom left). This is a reasonable assumption, since the superspeckles in the NACO PSF are mainly due to phase errors, which transform to symmetric pairs on either side of the PSF. Here we have made the conservative assumption that the possible range of C's flux should be from completely removing all residual flux at the position of C (Fig. 1, bottom right) to assuming there is a slightly brighter superspeckle at C's position (Fig. 1, top right).

3.1.1. Photometry of AB Dor C

The $K_s$ flux of AB Dor B is known from the Two Micron All Sky Survey (2MASS) catalog to be $K_s = 7.435$ (corrected for the 0.095 mag of contamination of B due to A's presence in the 2MASS 4" aperture photometry). Hence, by calibrating the mean $\Delta K_s$ of the PSF to Ba/Bb (which varied by less than 2% over a range of 1.5", 2.0", and 2.5" apertures), we derive $K_s = 9.50 \pm 0.16$ mag for C. This flux is derived assuming a symmetric PSF, while the large error bars are derived assuming minimal symmetry in the AB Dor A PSF and adding in the maximum errors of the aperture photometry (see Fig. 1, top and bottom right). Hence, the true flux of AB Dor C should certainly fall inside this range. Our new value of $K_s = 9.50 \pm 0.16$ is very similar to the 9.45$^{+0.060}_{-0.075}$ mag measured in Close et al. (2005). Our conservative assumption of minimal PSF symmetry around AB Dor A leads to our photometric errors' being larger than those of Close et al. (2005), where it was assumed that the PSF was mainly symmetric. Our new photometry is also consistent (if a bit brighter and more precise) than the 9.79$^{+0.33}_{-0.2}$ mag independently determined by Luhman & Potter (2006) from the Close et al. (2005) data set. Moreover, we obtain $K_s \sim 9.59$ mag from the IFS data cube in Paper I—adding further confidence to our $K_s$-band flux for C. Hence, there is now reasonable agreement from three different epochs that $K_s = 9.50$ mag for AB Dor C.

From the Hipparcos distance of 14.9 \pm 0.1 pc and the $-2.82 \pm 0.15$ mag K-band bolometric correction from Allen et al. (2003; appropriate for M5.5) and noting that for an M5.5 spectral type $K_s - K \sim 0.33$ mag (Daemgen et al. 2007), we derive a luminosity of $L = 0.0021 \pm 0.0005 L_\odot$ from the observed $K_s = 9.50 \pm 0.16$ mag of AB Dor C.

3.1.2. Astrometry of the AB Dor A/C System

From our PSF fitting, AB Dor C is found to be 0.219" \pm 0.008" at P.A. = 155.92° \pm 0.03°, in good agreement with the orbit of Nielsen et al. (2005), which predicts a separation of 0.2186" at P.A. = 155.17° for 2005 January 7 (2005.0170). This good agreement gives us further confidence in the orbital solution of Nielsen et al. Moreover, we have another (even later) 2006 January 24 (2006.0660) epoch of observation from the IFS data set of Paper I (see Table 1). This additional data point also fits the orbital solution of Nielsen et al. very well. Figures 2 and 3 illustrate the quality of the orbital solution of Nielsen et al. (2005). Note that this orbit was mainly determined by the reflex motion of component A from \sim 1 mas combined Hipparcos and VLBI.
### Table 1

**The AB Doradus System**

| Parameter                        | A                  | C                  | Ba                 | Bb                 |
|----------------------------------|--------------------|--------------------|--------------------|--------------------|
| $K_s$ magnitude                  | 4.686 ± 0.016      | 9.50 ± 0.16        | 8.08 ± 0.20        | 8.30 ± 0.20        |
| Separation$^a$ from A (arcsec)   | ...                | 0.219 ± 0.008      | 8.87 ± 0.10        | ...                |
| P.A.$^a$ with respect to A (deg) | ...                | 155.92 ± 0.50      | 346.31 ± 0.50      | ...                |
| Separation$^b$ from Ba (arcsec)  | ...                | ...                | 0.060 ± 0.003      | 246 ± 2            |
| P.A.$^b$ with respect to Ba (deg)| ...                | ...                | ...                | ...                |
| Separation$^c$ from A (arcsec)   | ...                | 0.202 ± 0.010      | ...                | ...                |
| P.A.$^c$ with respect to A (deg) | ...                | 180.78             | ...                | ...                |
| Period with respect to A (yr)    | ...                | 11.74 ± 0.07$^c$   | 1400–4300$^d$      | ...                |
| Period with respect to Ba (yr)   | ...                | ...                | ...                | ~0.9               |
| Spectral type                    | K1                 | M5.5 ± 1.0         | M3.5 ± 1.5         | M4.5 ± 1.5         |
| $T_{\text{eff}}$ (K)             | 5081 ± 50          | 2925 ± 170         | 3265 ± 245         | 3095 ± 255         |
| Luminosity ($L_\odot$)           | 0.388 ± 0.008      | 0.0021 ± 0.0005    | 0.008 ± 0.002      | 0.006 ± 0.002      |
| Mass ($M_\odot$)                 | 0.865 ± 0.034      | 0.090 ± 0.005$^c$  | <0.25$^d$          | <0.15$^d$          |
| System age (Myr)                 | 75 ± 25$^e$        |                    |                    |                    |
| System distance$^f$ (pc)         | 14.9 ± 0.1         |                    |                    |                    |

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* Observations made on 2005 January 7 UT (2005.0170).
* Observations made on 2006 January 24 UT (2006.0660).
* Orbital solution of Nielsen et al. 2005.
* Orbital calculations of Guirado et al. 2006.
* Age solution of Nielsen et al. 2005.
* Hipparcos distance (15.06 ± 0.11 pc is derived from Hipparcos and VLBI by Guirado et al. 2006).

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Fig. 1.—Top left: AB Dor C and A (unsharp-masked). Top right: After subtracting the PSF scaled by 4.5 times ($K_s = 9.66$ mag), there is too much residual light at the location of C; hence this is a lower limit to the flux of AB Dor C. Bottom left: A more optimal subtraction leaving the same amount of flux on either side of A ($K_s = 9.50$ mag). Bottom right: An oversubtraction of the PSF leading to an upper limit of the flux of C of $K_s = 9.34$. The lines bisect AB Dor A’s PSF and mark the location of AB Dor C.
11 months apart, could imply either a long-period orbit with a very large inclination angle, or else an orbital period close to 11 months.5 Thus, the two observations of the AB Dor Ba/Bb system, taken consistent with a Keplerian orbit with a period on the order of 1 yr.

Recently, Jeffers et al. (2007) have estimated the radial velocity variations of the AB Dor A/C system from 1988 to 1994. They find a reasonable fit of our older Close et al. (2005) orbital solution. The more recent orbital solution of Nielsen et al. (2005) should be similar. This is further proof of the quality of the A/C orbital solution.

3.1.3. Astrometry of the Ba/Bb System

We were also able to study the companion binary Ba/Bb (a tight 0.07", P.A. = 238.6° ± 0.3° binary discovered by Close et al. [2005]), which is visible some 9" away in the reduced image. On 2005 January 7, we find the Ba/Bb binary is now 0.060" ± 0.003" in separation at P.A. = 246° ± 2° (with ΔKs = 0.22 mag), while Ba is 8.87° ± 0.10° at P.A. = 346.31° ± 0.5° with respect to A (see Table 1 for more details). The small change in position of Bb with respect to Ba and A since the 2005 February 2 observations of Close et al. (2005) definitively proves that Ba/Bb is a tight binary itself bound to A. Previous observations show that B itself is in orbit around A (Guirado et al. 2006).

Although we know relatively little about the orbit of Bb around Ba, we know that AB Dor Ba/Bb has a projected separation of 0.9 AU, and for an almost equal mass binary with combined spectral type ~M4 (Martin & Brandner 1995; see Table 1), this is consistent with a Keplerian orbit with a period on the order of 1 yr. Thus, the two observations of the AB Dor Ba/Bb system, taken 11 months apart, could imply either a long-period orbit with a very large inclination angle, or else an orbital period close to 11 months.5

3.2. Spectral Type of AB Dor C

As outlined in Paper I, an excellent R ~ 1500 H and Ks spectrum of AB Dor C was obtained with the SINFONI IFS. Here we attempt to place our spectrum on a spectral sequence. Unfortunately, there simply are no good H and K template spectra for late-M stars of ~75 Myr age. Hence, we have endeavored to fit our spectrum to young (~1 Myr; Gorlova et al. 2003) and old field M stars (Cushing et al. 2005). As is clear from Figures 4–7, there is pretty good agreement that the spectrum is similar to an M5 or M6.

We feel that the spectra presented here are superior to those previously published by Close et al. (2005), Nielsen et al. (2005), and Luhan & Potter (2006) for several reasons. All previous published spectra were different reductions of the Close et al. (2005) long-slit NACO K-band spectra. These AO-fed long-slit spectra suffered from many of the potential drawbacks of AO-fed long-slit spectra. First, the very small 0.085" slit used in the older spectra was only roughly aligned with the binary, because of flexure, etc. Hence, there are different slit losses for each spectrum obtained as AB Dor was nodded along the slit. Moreover, the core FWHM of the AO PSF decreases as λ increases, and hence slit losses are also a function of the wavelength as well as the centering error. Finally, there may have been some error in the position angle of the slit, and so there may be different slit losses between AB Dor A and C. Also, the very small separation of 0.15" between A and C made these spectra very difficult to reduce (in fact, many of the individual spectra had to be dropped from the reduction, since no manner of subtracting component A could reveal a non-noise signal at the position of C). Indeed, Luhan & Potter (2006) and Nielsen et al. (2005) only used ~50% of the spectra obtained to try to detect a signal from C. In all these previous spectra, the flux from AB Dor A swamped the light from C (just 0.15" away); this is not surprising, given the ~0.2" images obtained with the NACO spectrograph that night. In the end, none of the three previous efforts at reducing the Close et al. (2005) spectral data set could obtain any meaningful K continuum of AB Dor C (and no H-band spectra were attempted). So, all these past efforts simply

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5 But see note added at the end of this paper.
fitted the "continuum" with a polynomial and attempted to remove as much of it as possible (in Close et al. [2005], the continuum was restored with a standard). Therefore, no spectrum of AB Dor C with the original continuum intact has been published to date.

Without continua it is very hard to be sure that one is not either over- or undersubtracting A from C. Hence, strengths of the CO and Na absorption lines are somewhat suspect and uncertain. This explains, in part, the significant dispersion in the spectral types determined from the three different reductions of the rather poor-quality AO long-slit spectra. To better understand what the real spectral type of AB Dor C is, we have approached this problem with the new (more advanced) technique of PSD IFS reduction.

Our IFS spectrum in this paper is superior for several reasons. One is that C was a more favorable 0.20" away from A at the time of the IFS observation. Another is that use of the IFS allowed significantly better removal of the contaminating PSF wing of A (at every wavelength) from the IFS data cube by PSF subtraction (see Paper I for full details). Moreover, we could easily check in each IFS "image" how well we had removed the wing of A from the position of C (this is nearly impossible to do with long-slit spectra). Also, by effectively integrating longer, we were able to obtain S/N ~ 40. In addition, we have obtained both H-band and K-band spectra. Increasing the spectral range through H helps determine a more accurate spectral type. Finally, use of the IFS eliminates slit losses and has allowed us to produce excellent spectra of AB Dor C in the H and K bands with a stable continuum across both bands. To highlight the improvement, we directly compare our new spectrum with that of Nielsen et al. (2005) in Figure 3 of Paper I.

We believe that the points raised above make clear why our H and K IFS continuum-preserved spectrum is superior to previously published (non-continuum-preserved) K spectra of AB Dor C. However, it is still difficult to obtain a perfect spectral type fit for AB Dor C, since it has an age (and, so, surface gravity) different from that of published M standards. For example, in Figure 5 it is clear that M4 is not the correct spectral type, because the Na lines of Gl 213 fit the AB Dor C spectrum too well—since AB Dor C is younger than Gl 213, it should have weaker Na lines than a field dwarf of the same spectral type (see, e.g., Gorlova et al. 2003). In fact, the M5 field dwarf Gl 51 fits the CO lines the best (including an exceptionally good fit to the pseudoc continuum past 2.3 μm). Since CO is not strongly gravity dependent (Gorlova et al. 2003), there is evidence that the temperature of AB Dor C must be close to that of Gl 51 (M5).

The spectra presented in previous studies all likely had too much strength in the Na line compared with CO (which is unlikely for a low surface gravity object). From this study it is now clear that in the K-band data, AB Dor C appears as a low surface gravity M5 (fitting the CO well but weaker in the Na lines). Moreover, our K-band continuum follows that of GI 51 (M5) or Gl 406 equally well, yet that of an M4 (too hot) or M7 (too cold) can be excluded at better than 1 σ of our estimated noise level (see the 1 σ error bars in Figs. 5 and 6). Hence, there is excellent evidence from Figure 5 that the spectral type of C must be in the range M5–M6.

Further evidence comes from Figure 6 (our H-band spectrum). Here one can see that the Mg and Al lines between 1.65 and 1.75 μm of the M3 and M4 dwarfs are not visible in the cooler AB Dor C atmosphere. Moreover, AB Dor C’s continuum shape is nicely matched by the M5 and M6 templates from 1.58 to 1.8 μm, whereas the bluest part of H has the lowest Strehl ratio and likely some slight contamination from the hotter A component—heating up our continuum slightly at the bluest part of the H band. The M7
continuum appears too cool. Hence, we see that in the $H$ band, the best fit is to an M5–M6 spectral type. Therefore, we determine that the gravity-independent line strengths (such as CO) and the continuum of AB Dor C are best fitted by field M5–M6 dwarfs. In summary, we conservatively estimate a spectral type of M5.5 ± 1.0 for AB Dor C.

Our new spectral type is considerably earlier than the M8 ± 1 measured in Close et al. (2005) and Nielsen et al. (2005), yet it is consistent with the M6 ± 1 independently derived by Luhman & Potter (2006). In summary, our continuum is preserved and the S/N (~40), wavelength range, and resolution (~1500) are much higher, and hence the spectrum presented here is a significant improvement over any previous spectrum of AB Dor C.

Using the dwarf temperature scale of Leggett et al. (1996), we find a temperate range of $T_{\text{eff}} = 2925^{+170}_{-140}$ K for AB Dor C. However, this error does not take into account a possible ~150 K systematic error in this popular temperature scale. Hence, the final total errors could be as high as $2925^{+226}_{-205}$ K.

4. COMPARISON WITH MODELS

In Figure 7, we compare our observed values with those predicted by the cooling curves of the DUSTY models (Chabrier et al. 2000). Note how the $J$- and $H$-values appear to be fainter than the models would predict (assuming a 75 Myr age for AB Dor; Nielsen et al. 2005); this result is similar to that of Close et al. (2005). Yet there is good agreement with the $K_s$ (as was also the case in Close et al. 2005). Moreover, our higher $T_{\text{eff}}$ is in better agreement with the cooling curves than in Close et al. (2005).

It is interesting to note that the $J - K_s$ color for AB Dor C is $\sim 1.26 \pm 0.21$, which is surprisingly red for an M5.5 object (which are typically closer to $J - K_s \sim 1.0$ in the Pleiades). Hence, it is possible that the $J$-band flux measured in Close et al. (10.76 ± 0.1 mag) or that measured by Luhman & Potter (10.72 ± 0.42 mag)
may be systematically too faint. We caution that it is problematic to obtain high-quality, high-contrast images in the J band with AO, and so in general, weight should not be placed on J-band fluxes of faint companions, since lower Strehl ratios lead to a higher chance of a poor flux calibration. In any case, the mean J flux of Close et al. (2005) would only have to be brightened by ~0.2 mag to yield colors consistent with M5.5 Pleiades objects. This would lead to slightly better agreement with the models, especially at the oldest ages suggested for AB Dor of 75–150 Myr by Luhman et al. (2005).

As mentioned by Luhman et al. (2005), a good technique for indirectly determining the mass of an object is to place the object in the H-R diagram and from the evolutionary tracks estimate a mass. In Figure 8, we show how the new spectral type of M5.5 is in good agreement with the DUSTY tracks in the H-R diagram for a 0.090 $M_\odot$ object like AB Dor C. Hence, the combination of a careful measurement of the $K_s$ flux and spectral type can allow the mass of a young low-mass object such as AB Dor C to be estimated from the DUSTY tracks. However, underestimates of the mass can occur without proper (continuum-preserved) spectra or if one relies on $H$ and $J$ fluxes alone.

The points with error bars in Figure 8 mark all low-mass young objects with well-determined dynamical masses. The thick diagonal lines represent the rough disagreement between the measured luminosity and temperature and the values actually predicted by the DUSTY models for the true mass of the object. One can see that for AB Dor C and the older (~300 Myr) Gl 569B system (Zapatero Osorio et al. 2004), the offsets between observation and the tracks are within the 1 $\sigma$ uncertainties (especially considering the uncertainty in the ages for these systems). There is somewhat less agreement for the secondary of the very young 2M0535 eclipsing binary system in Orion (Stassun et al. 2006).

FIG. 8.—H-R diagram showing low-mass Pleiades objects from Martin et al. (2000; four-pointed stars), other low-mass members of the Pleiades taken from the literature (three-pointed stars), and AB Dor Ba/Bb (squares). The dashed “vertical” lines are isomass contours for the DUSTY models (left to right, 0.09, 0.07, 0.05, 0.04 $M_\odot$), while the more “horizontal” lines are the DUSTY isochrones (top to bottom, 1, 10, 50, 100, 120, 500, 1000 Myr). Note that the DUSTY models predict that a 75 Myr object of 0.09 $M_\odot$ should be similar in temperature and luminosity to that observed. From the location of AB Dor C on the H-R diagram, one would derive a mass of ~0.09 $M_\odot$, a good estimate of the measured mass. As the temperature (dwarf T_eff scale of Leggett et al. 1996; Luhman 1999) and luminosities (BCs from Allen et al. 2003) of the Pleiades objects in this plot were determined in the same manner used for AB Dor C, and these Pleiades points mostly fall along the appropriate 120 Myr DUSTY isochrone (dotted line), we are assured that our temperature scale and bolometric correction are reasonable. The points with error bars mark all known low-mass young objects with well-determined dynamical masses, with 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 AB Dor C and the older (300 Myr) Gl 569B system (Zapatero Osorio et al. 2004), the offsets between observation and the tracks are within the 1 $\sigma$ uncertainties (especially considering the uncertainty in the ages for these systems).

However, in the recently discovered eclipsing binary 2MASS J05352184–0546085 (hereafter 2M0535; Stassun et al. 2006) in the Orion Trapezium star formation region (~1 Myr age), the 0.034 ± 0.0027 $M_\odot$ secondary is hotter than the 0.0541 ± 0.0046 $M_\odot$ M6.5 primary. Hence, there is an increase in uncertainty in the models for very young (>10 Myr), low-mass (<0.040 $M_\odot$) objects. However, the derived mass for 2M0535A would only be low by ~25% (just consistent with the 1 Myr track), whereas the derived mass for 2M0535B from the 1 Myr track would be about 200% too high (a similar trend was predicted by Mohanty et al. 2004).

Note added in manuscript.—We have also obtained an acquisition image of AB Dor Ba and Bb from the ESO VLT archive between the two observational epochs discussed here. This image [from ESO program 073.C-0469(B), G. Chauvin et al.] was taken on 2004 September 24: about $\frac{1}{2}$ months after the Close et al. (2005) data set, and about $\frac{1}{2}$ months prior to the Neuhauser et al. (2005) data set. In this image, taken with the same NACO system, using the same S13 camera with identical plate scale and the same $K_s$ filter, and with AB Dor Ba/Bb having a similar FWHM compared with future and past epochs, the appearance of the binary is drastically different. Unlike the 2004 February and 2005 January images, where the two components of the binary are clearly distinguishable, the 2004 September image appears to be of a single star. This short-period variation, combined with the similar
separations and position angles observed between 2004 February and 2005 January, seems to constrain the orbit of the AB Dor Ba/Bb system to approximately 11 months. Future monitoring of this system is required in order to obtain more detailed orbital parameters.

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