2MASS 22344161+4041387AB: A WIDE, YOUNG, ACCRETING, LOW-MASS BINARY IN THE LkHα233 GROUP*

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ABSTRACT

We report the discovery of a young, 0.16 binary, 2M2234+4041AB, found as the result of a Keck laser guide star adaptive optics imaging survey of young field ultracool dwarfs. Spatially resolved near-infrared photometry and spectroscopy indicate that the luminosity and temperature ratios of the system are near unity. From optical and near-infrared spectroscopy, we determine a composite spectral type of M6 for the system. Gravity-sensitive spectral features in the spectra of 2M2234+4041AB are best matched to those of young objects (∼1 Myr old). A comparison of the Teff and age of 2M2234+4041AB to evolutionary models indicates that the mass of each component is 0.10−0.07 M⊙. Emission lines of Hα in the composite optical spectrum of the system and Brγ in spatially resolved near-IR spectra of the two components indicate that the system is actively accreting.

Both components of the system have IR excesses, indicating that they both harbor circumstellar disks. Though 2M2234+4041AB was originally identified as a young field dwarf, it lies 1.5 from the well-studied Herbig Ae/Be star, LkHα233. The distance to LkHα233 is typically assumed to be 880 pc. It is unlikely that 2M2234+4041AB could be this distant, as it would then be more luminous than any known Taurus objects of similar spectral type. We re-evaluate the distance to the LkHα233 group and find a value of 325 ± 75 pc, based on the Hipparcos distance to a nearby B3-type group member (HD 213976). 2M2234+4041AB is the first low-mass star to be potentially associated with the LkHα233 group. At a distance of 325 pc, its projected physical separation is 51 AU, making it one of the growing number of wide, low-mass binaries found in young star-forming regions.

Key words: binaries: visual – infrared: stars – stars: formation – stars: low-mass, brown dwarfs

Online-only material: color figures

1. INTRODUCTION

The binary fractions, mass ratios, and separations of very low mass (VLM; M < 0.1 M⊙) binaries can provide critical tests to theories of VLM star and brown dwarf formation. In addition to the same mechanism that forms low-mass stars, there is a number of suggested processes for forming brown dwarfs (Whitworth et al. 2007). These include gravitational instabilities in massive circumstellar disks (e.g., Stamatellos & Whitworth 2009), turbulent or gravitationally enhanced fragmentation (e.g., Padoan & Nordlund 2004; Bonnell et al. 2008), ejection from protostellar embryos (e.g., Bate & Bonnell 2005; Clarke et al. 2001), and photoevaporation of protostellar cores (Whitworth & Zinnecker 2004). These various formation mechanisms proposed for brown dwarfs are expected to result in differing binary fractions, mass ratios, and separations.

To date, imaging surveys for VLM binaries have focused on field (≥1 Gyr old) objects (e.g., Burgasser et al. 2006; Goldman et al. 2008; Reid et al. 2006; Siegler et al. 2005; M. C. Liu et al. 2009, in preparation), and have found much lower binary fractions (7%–15% reported by Burgasser et al. 2007; 20% if corrected for completeness; Allen 2007) than found for solar-type field stars (44%, Duquennoy & Mayor 1991). The detected field VLM binaries also tend to be tightly bound and in nearly equal mass systems, whereas higher mass field binaries have a much wider range of separations and mass ratios. It is difficult, however, to robustly test models of brown dwarf formation with field binary statistics for a number of reasons. First, wide VLM binaries could be dynamically disrupted by the time the systems reach the age of the field population (Close et al. 2007). Additionally, the intrinsic faintness and large changes in luminosity with mass for field objects (e.g., Baraffe et al. 2003) mean that low-mass ratio systems were unlikely to be detected by existing high-resolution imaging surveys. Lastly, the field population is comprised of objects that were formed in a variety of star-forming regions with varying initial conditions, so comparison to model calculations for brown dwarfs forming in a single molecular cloud may be inappropriate.

To provide a better test of brown dwarf and star formation models, one would like to compare the binary properties of young, VLM objects to model predictions. The statistics for young, low-mass binaries are still uncertain. Ahmic et al. (2007) combined their survey with results from Kraus et al. (2005, 2006) and Konopacky et al. (2007) and report a combined binary fraction of 7 ± 5% for 72 young, low-mass stars and brown dwarfs. This binary fraction is similar to the binary fraction for...
field VLM binaries (7%–15%, Burgasser et al. 2007). However, because the nearest star-forming regions are \( \sim 125 \) pc away, only wide binaries can be detected by current imaging surveys. The Ahmic et al. (2007) binary fraction is valid only for young VLM binaries with separations greater than 8 AU, whereas field VLM binaries tend to have tighter separations (Burgasser et al. 2007). Thus, the actual young binary fraction would be significantly higher than the fraction found for field VLM binaries, if surveys for young and field VLM binaries reached the same physical separation limits. Young star-forming regions also show an interesting population of very wide separation (\( \gtrsim 100 \) AU), loosely bound VLM binaries (Béjar et al. 2008; Bouy et al. 2006; Close et al. 2007; Luhman 2004a). The fate of these wide binaries is unknown, as it is unlikely that they could survive ejection or dispersal from their natal clouds, given their low binding energies.

To probe the multiplicity properties of young VLM objects at tight separations and look for wide systems in the field that have not yet dissolved, we are carrying out a Keck laser guide star adaptive optics (LGS AO) survey to image young (\( \lesssim 100 \) Myr), field VLM objects. This paper presents the first results of this program. This survey is a part of our larger, ongoing effort using LGS AO to study the multiplicity of VLM objects and determine their fundamental properties (e.g., Dupuy et al. 2009; Liu et al. 2008, 2006).

Young field objects are usually found in three ways: as companions to known young field stars (Rebolo et al. 1998), via association with known young moving groups (e.g., Gizis 2002), or serendipitously as a part of searches for older field dwarfs (e.g., Kirkpatrick et al. 2008). 2MASS J22344161+4041387 (hereinafter 2M2234+4041AB) was identified by Cruz et al. (2003) as a candidate young M6-type object. They classified the object as young on the basis of weak CaH (6750–7050 Å) and K\( i \) doublet (7665 and 7699 Å) absorption and strong H\( \alpha \) emission seen in its low-resolution optical spectrum.

Using Keck LGS AO, we have discovered 2M2234+4041AB to be a binary system. In this paper, we present multiwavelength imaging and spectroscopy used to determine the properties of 2M2234+4041AB.

2. OBSERVATIONS

2.1. Keck LGS AO/NIRC2 Imaging

We imaged 2M2234+4041AB on three epochs from 2006 to 2008 using the LGS AO system (Wizinowich et al. 2006; van Dam et al. 2006) of the 10 m Keck II Telescope on Mauna Kea, Hawaii. We used the facility IR camera NIRC2 with its narrow field-of-view camera, which produces a 10" × 10" field of view, and the Mauna Kea Observatories J, H, K\( S \), and L\( \prime \) filters (Simons & Tokunaga 2002; Tokunaga et al. 2002). Images of 2M2234+4041AB are presented in Figure 1. Setup time for the telescope to slew to the science target and for the LGS AO system to be fully operational varied from 4 to 21 minutes on the observing runs. The LGS brightness was equivalent to a V \( \approx 9.4–10.1 \) mag star, as measured by the flux incident on the AO wavefront sensor. The LGS provided the wavefront reference source for AO correction, with the exception of tip-tilt motion. Tip-tilt aberrations and quasi-static changes in the image of the LGS as seen by the wavefront sensor were measured contemporaneously with a second, lower-bandwidth wavefront sensor monitoring 2M2234+4041AB itself (\( R = 16.8 \); Monet et al. 2003). The sodium laser beam was pointed at the center of the NIRC2 field of view for all observations.

For the JHK\( S \) filters, we obtained a series of dithered images, offsetting the telescope by a few arcseconds. The resulting images were reduced in the standard fashion (dome flat-fielded, median sky-subtracted, registered, and stacked). The L\( \prime \)–band data were observed and reduced in a similar fashion, except that the flat fields were constructed from the science frames themselves and sky subtraction was done in a pairwise fashion using consecutive frames.

To measure the flux ratios and relative positions of the binary’s two components, we used an analytic model of the point-spread function (PSF) as the sum of three elliptical Gaussians. For the individual images obtained with each filter, we fitted for the flux ratio, separation, and position angle (PA) of the binary. The averages of the results were adopted as the final measurements and the standard deviations as the errors. The relative astrometry was corrected for instrumental optical distortion based...
on analysis by B. Cameron (2007, private communication) of images of a precisely machined pinhole grid located at the first focal plane of NIR2. Since the binary separation and the imaging dither steps are relatively small, the effect of the distortion correction is minor.

In order to gauge the accuracy of our measurements, we created myriad artificial binary stars from images of single stars, chosen to have comparable Strehl and FWHM as the science data. For each filter, our fitting code was applied to artificial binaries with similar separations and flux ratios as 2M2234+4041AB over a range of PAs. These simulations showed that any systematic offsets in our fitting code are very small, well below the random errors, and that the random errors are accurate. In cases where the rms measurement errors from the artificial binaries were larger than those from the 2M2234+4041AB measurements, we conservatively adopted the larger errors. The exception was the L'-band data, where the prominent first Airy ring seen in the images coincides with the separation of the binary. The results from the simulated L'-band binaries indicated a significant (1.5σ) shift in the astrometry, so this was applied to the raw measurements; the shift moves the L'-band astrometry into better agreement with the JHKs results.

To convert the instrumental measurements of the binary’s separation and PA into celestial units, we used a weighted average of the calibration from Pravdo et al. (2006), with a pixel scale of 9.963 ± 0.011 mas pixel⁻¹ and an orientation for the detector’s +y-axis of 0:13 ± 0:07 east of north for NIR2’s narrow camera optics. These values agree well with Keck Observatory’s notional calibrations as well as the 9.963 ± 0.005 mas pixel⁻¹ and 0:13 ± 0:02 reported by Ghez et al. (2008).

Table 1 presents our final Keck LGS imaging measurements.

2.2. IRTF/SpeX Near-IR Spectroscopy and L’ Imaging

Near-IR spectroscopy of 2M2234+4041AB was obtained on 2008 June 25 (UT) using the SpeX spectrograph (Rayner et al. 2003) on the NASA Infrared Telescope Facility. The seeing recorded by the IRTF was 0.6. Six cycles of 180 s exposures were taken, nodding along the slit, for a total integration time of 36 minutes. The data were taken in the SXD mode with a 0.3 slit (aligned with the parallactic angle) producing a 0.9–2.5 μm spectrum with a resolution (λ/Δλ) of ~2000. For telluric and flux correction, we observed a nearby A0V star, BD+39 4890 (V = 9.47 mag) and obtained calibration frames (flats and arcs) prior to our observations of 2M2234+4041AB. For comparison to our spectrum of 2M2234+4041AB, we obtained SpeX spectra of USco CTIO 75 (M6, Ardila et al. 2000) on 2008 June 25 and spectra of Haro 6-32 (M5, Luhman 2004b), CFHT-BD-Tau 18 (M6, Guieu et al. 2006), and CFHT-BD-Tau 4 (M7, Luhman 2004b) on 2005 October 22. We used the same instrument setup as for our spectrum of 2M2234+4041AB, and obtained total integration times of 20–30 minutes per source. The spectra were reduced using SpeXtool (Cushing et al. 2004), the facility reduction pipeline, which includes a correction for telluric absorption following the method described in Vacca et al. (2003). Our SpeX spectra are presented in Figures 2 and 3.

To obtain integrated-light L’ photometry (in the MKO system; Simons & Tokunaga 2002; Tokunaga et al. 2002) of 2M2234+4041AB (Table 2), we obtained images on 2008 September 24 (UT) using the SpeX guider camera. Conditions were photometric and the IRTF recorded a seeing of ~0.6. We obtained a set of 10 nodded cycles of 300 s exposures, nodding the telescope 7.7 in the north–south direction. We repeated this process for two additional positions. Between sets of 2M2234+4041AB images, we obtained images of the UKIRT faint standard FS2–27, using the same instrument and observing configuration. To flat field our images, we used the median of dome flats for the J, H, K, and HK filters (kindly provided to us by John Rayner). We subtracted each nodded pair, and median

Table 1

| Date (UT) | Filter | Air mass | FWHM (mas) | Strehl Ratio | Separation (mas) | Position Angle (deg) | Δmag |
|-----------|--------|----------|------------|-------------|-----------------|---------------------|------|
| 2006 Oct 14 | $K_s$ | 1.50 | 78 ± 5 | 0.18 ± 0.02 | 158.5 ± 0.6 | 99.3 ± 0.3 | 0.05 ± 0.03 |
| 2007 Sep 6 | $J$ | 1.08 | 37.2 ± 0.8 | 0.116 ± 0.005 | 158.2 ± 0.3 | 99.52 ± 0.09 | 0.06 ± 0.03 |
| $H$ | 1.07 | 40.8 ± 0.7 | 0.161 ± 0.008 | 158.5 ± 0.3 | 99.53 ± 0.15 | 0.096 ± 0.010 |
| 2008 Sep 8 | $L’$ | 1.07 | 93 ± 3 | 0.58 ± 0.07 | 158.2 ± 1.0 | 100.1 ± 0.3 | 0.23 ± 0.03 |

Notes. The tabulated uncertainties are the rms of the measurements. The astrometric errors are computed by appropriately combining in quadrature: (1) the instrumental measurements from fitting the images of the binary (with errors derived from fitting of simulated binary images) and (2) the overall uncertainties in the NIRC2 pixel scale and orientation. See Section 2.1 for details.

aAll photometry on the MKO system.

Figure 2. Composite SpeX spectrum of 2M2234+4041AB (black) compared to young Taurus objects with optical spectral types of M5 (Haro 6-32, blue), M6 (CFHT-BD-Tau 18, red), and M7 (CFHT-BD-Tau 4, green). The spectra of Taurus objects are smoothed to λ/Δλ ~ 500 and dereddened (using the reddening law of Fitzpatrick 1999) by $A_V$’s reported in Guieu et al. (2006) and Luhman (2004b). Spectral type sensitive features are labeled. The spectrum of 2M2234+4041AB (particularly its H₂O features) is best matched by a young Taurus M6. (A color version of this figure is available in the online journal.)
2M2234+4041AB.

with the line depths seen in the Taurus M6, implying an age of 

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depths of the alkali lines in the spectrum of 2M2234+4041AB agree quite well

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TW A8B, green), and a

\[ \sim \]

∼ 10 Myr old TWHydra M5

(TWASB, green), and a ∼1 Gyr field M6 (G1406, magenta), all obtained with IRTF/SpecX. Each spectrum is normalized by its median flux from 1.1 to 1.3 μm.

The depths of the Kt and NaI alkali lines (labeled) increase with age. The depths of the alkali lines in the spectrum of 2M2234+4041AB agree quite well with the line depths seen in the Taurus M6, implying an age of ∼1 Myr for 2M2234+4041AB.

(A color version of this figure is available in the online journal.)

Figure 4. OSIRIS K-band spectra of 2M2234+4041A (black) and B (gray) compared to a ∼1 Myr old Taurus M6 (CFHT-BD-Tau 18, blue) and a ∼1 Gyr field M6 (G1406, magenta). Each spectrum is normalized by its median from 2.0 to 2.4 μm. The 2.2 μm NaI alkali lines in components A and B are much weaker than for the field dwarf, indicating that both components are young. The continuum shape and 2.3 μm CO bandhead for components A and B are remarkably similar, in agreement with their identical spectral classification of M6.

(A color version of this figure is available in the online journal.)

combined the resulting images at each position, for six final images of 2M2234+4041AB and four final images of FS2–27.

We obtained aperture photometry for both 2M2234+4041AB and FS2–27 using an aperture radius of 1′′.

We acquired two optical spectra of 2M2234+4041AB on 2008 June 30 (UT) using the OSIRIS Spectrometer (HIRES; Vogt et al. 1994) on the Keck I telescope. We selected the 20 mas pixel−1 scale for our observations. We observed 2M2234+4041AB taking eight dithered exposures of 120 s each, for a total of 16 minutes on source integration. The FWHM, as measured on the stacked two-dimensional images of 2M2234+4041AB, was 68 ± 2 mas, thus the binary (158 mas separation) is well resolved. Immediately following our observations of 2M2234+4041AB, we obtained sky frames using the same dither pattern and integration time. To correct for telluric absorption, we obtained spectra of a nearby A0V star, HD 209932. The initial reduction from two-dimensional images to three-dimensional data cubes was accomplished using the OSIRIS data reduction pipeline (Krabbe et al. 2004). The individual spectra for each component were then extracted from the three-dimensional data cubes by summing the flux in fixed apertures of 175 × 175 mas at each wavelength. The resulting spectra of each component were then median combined together. Telluric correction and flux calibration were performed using the observations of the A0 V standard and the technique described in Vacca et al. (2003). The resulting 1.96–2.38 μm spectra of 2M2234+4041A and B (Figure 4) have a resolution (Δλ/Δλ) of ∼3500, and median signal-to-noise ratio (S/N) of ∼90 pixel−1.

2.4. Keck HIRES Optical Spectroscopy

We acquired two optical spectra of 2M2234+4041AB on May 11 and August 12 of 2006 with the High Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994) on the Keck I telescope. We used the O’861 slit with HIRES to give a spectral resolution of λ/Δλ ≈ 58000. To maximize the throughput near the peak of a M dwarf spectral energy distribution, we used the GG475 filter with the red cross-disperser.

Each stellar exposure was bias-subtracted and flat-fielded for pixel-to-pixel sensitivity variations. After optimal extraction, the one-dimensional spectra were wavelength calibrated with a Th/Ar arc. Finally, the spectra were divided by a flat-field response and corrected to the heliocentric rest frame. The final spectra were of moderate S/N reaching ∼25 pixel−1 at 7000 Å.

We cross-correlated each of 7 orders between 7000 and 9000 Å of each stellar spectrum with a radial velocity (RV) standard of similar spectral type using IRAF’s fxcor routine

Notes

\[ a \]

Calculated from composite photometry using A mag from Table 1.

\[ b \]

From the 2MASS All-Sky Point Source Catalog (Cutri et al. 2003).

Table 2

| Band | Photometry of 2M2234+4041AB |
|------|----------------------------|
|      | A+B | A | B |
|      | (mag) | (mag) | (mag) |
| \( J \) | 12.57 ± 0.02 | 12.39 ± 0.02 | 13.35 ± 0.03 |
| \( H \) | 11.83 ± 0.02 | 12.54 ± 0.02 | 12.63 ± 0.02 |
| \( K_s \) | 11.44 ± 0.02 | 12.17 ± 0.02 | 12.22 ± 0.03 |
| \( L' \) | 10.52 ± 0.06 | 11.16 ± 0.06 | 11.39 ± 0.06 |

2.3. Keck LGS AO/OSIRIS Spectroscopy

We obtained spatially resolved \( K \)-band spectroscopy of 2M2234+4041AB on 2008 June 30 (UT) using the OSIRIS integral field spectrograph (Larkin et al. 2003) and LGS AO on the Keck-II telescope. We selected the 20 mas pixel−1 scale for our observations. We observed 2M2234+4041AB taking eight dithered exposures of 120 s each, for a total of 16 minutes on source integration. The FWHM, as measured on the stacked two-dimensional images of 2M2234+4041AB, was 68 ± 2 mas, thus the binary (158 mas separation) is well resolved. Immediately following our observations of 2M2234+4041AB, we obtained sky frames using the same dither pattern and integration time. To correct for telluric absorption, we obtained spectra of a nearby A0V star, HD 209932. The initial reduction from two-dimensional images to three-dimensional data cubes was accomplished using the OSIRIS data reduction pipeline (Krabbe et al. 2004). The individual spectra for each component were then extracted from the three-dimensional data cubes by summing the flux in fixed apertures of 175 × 175 mas at each wavelength. The resulting spectra of each component were then median combined together. Telluric correction and flux calibration were performed using the observations of the A0 V standard and the technique described in Vacca et al. (2003). The resulting 1.96–2.38 μm spectra of 2M2234+4041A and B (Figure 4) have a resolution (Δλ/Δλ) of ∼3500, and median signal-to-noise ratio (S/N) of ∼90 pixel−1.

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| \( L' \) | 10.52 ± 0.06 | 11.16 ± 0.06 | 11.39 ± 0.06 |
The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions.

(Fitzpatrick 1993). We excluded the Ca ii infrared triplet (IRT) and regions of strong telluric absorption in the cross-correlation. RVs and relevant line equivalent widths measured from our HIRES data are listed in Table 3, and portions of our HIRES spectrum are displayed in Figures 5 and 6. Further details of HIRES data reduction and analysis are provided by Shkolnik et al. (2009).

2.5. Proper Motion

To calculate a proper motion for 2M2234+4041AB, we used red and blue POSS-I images from the Digitized Sky Surveys and 12 i′- and z′-band images from the Tektronix 2048 × 2048 CCD camera (Tek) on the University of Hawaii 2.2 m telescope kindly provided to us by Roy Gal. 2M2234+4041AB is well detected (> 3σ) in all of the POSS-I and Tek images. The red and blue POSS-I images were taken on 1952 July 20 and have pixel scales of 1.77 and 1′/0 pixel−1, respectively. The Tek images were taken on 2007 July 31 and have a pixel scale of 0′′.22 pixel−1. We used Source Extractor (Bertin & Arnouts 1996) to obtain the x and y positions of objects in individual images and used IRAF’s xyyymatch and geomap routines (with third-order polynomial fits) to match detections within each epoch and spatially transform the detections to the image coordinate system of the POSS-I red image (for POSS-I epoch images) or the first Tek image (for all Tek images). The standard deviations of the fits found by geomap were ~0′.04 for the match of POSS-I red and blue images and ~0′.04 for the match of the Tek images. We then calculated the average x and y positions within each epoch, and used xyyymatch and geomap to match 107 sources and transform their POSS-I detected positions to the Tek image (x, y) coordinate system, giving us the Δx and Δy of 2M2234+4041AB. We then calculated the pixel scale and orientation of the Tek images using SCAMP (the Terapix astrometric software package), and converted Δx and Δy for 2M2234+4041AB to Δα and Δδ. The standard deviations found by geomap for transforming the POSS-I detections to the Tek image coordinate system were 0′′.34 in x and 0′′.27 in y. The measured motion of 2M2234+4041AB from the POSS-I images to the Tek images is ~58 ± 340 mas and 166 ± 270 mas, respectively, resulting in a proper motion of ~1 ± 6 and 3 ± 5 mas yr−1 for μαcos(δ) and μδ, respectively. Thus, 2M2234+4041AB shows no significant proper motion (Figure 7).

3. ANALYSIS

3.1. Spectral Type

We derive an optical spectral type by visually comparing the TiO and VO bands in our HIRES spectrum of 2M2234+4041AB to standard stars of known spectral types. For stars of spectral type ~M5.5 or later, the 7140 Å TiO band weakens due to condensation onto grains whereas the VO band at 7300 Å strengthens with spectral type until M7, and then weakens for later types. This allows us to unambiguously classify 2M2234+4041AB as M6 with a conservative uncertainty of ±1 subclass. The M6 optical spectral type we determine agrees with that of Cruz et al. (2003), who used low-resolution (R ≃ 1400) optical spectra.

We can also determine the spectral type of 2M2234+4041AB by comparing its SpeX near-IR spectrum to spectra of young objects in Taurus (Figure 2). We choose Taurus objects rather than field dwarfs for comparative spectral typing, as the spectral features of 2M2234+4041AB are consistent with a young age (see Section 3.3). Our near-IR spectrum of 2M2234+4041AB

(2006 May 11 (black) and 2006 August 12 (gray). The profiles have been continuum-subtracted and normalized at the peak flux of the line. The dotted line shows the 10% flux level. The Hα line equivalents widths and 10% widths imply ongoing mass accretion, and thus a young age for 2M2234+4041AB.
Figure 7. Proper motion of 2M2234+4041AB (filled star), as measured from POSS-I images (1952 July 20) and UH 2.2 m images (2007 July 31). The gray open circles show the proper motions measured for objects matched in the two epochs of images. The uncertainty (shown in the upper right) is the standard deviation found when transforming the POSS-I detected positions to the Tek image coordinates, divided by the time baseline.

is a near perfect match to the spectrum of CFHT-BD-Tau 18, a young Taurus object with an optically determined spectral type of M6 (Guieu et al. 2006). The spectral type sensitive index \((F_{\lambda}=1.550-1.560)/F_{\lambda}=1.492-1.502)\) of Allers et al. (2007), which is calibrated for young and field stars with optical spectral types, suggests a spectral type of M6.4 ± 1, in agreement with the spectral types we determine from visual inspection of optical and near-IR spectra. We assign a spectral type of M6 ± 1 to both components of 2M2234+4041AB given the similarity of their near-IR colors (Table 1) and K-band spectra (Figure 4).

3.2. Extinction

To obtain intrinsic colors and magnitudes of 2M2234+4041AB we must determine the amount of dust attenuating the source. To compute the extinction, we compare the observed \(J-H\) color of 2M2234+4041AB to the colors of field and young objects. We choose to determine our extinction value using \(J-H\) for two reasons. First, of the available photometry of 2M2234+4041AB (Table 2), the \(J-H\) color is at the shortest wavelength and hence is the most sensitive to extinction, and the least likely to be contaminated by excess emission from a circumstellar disk. Second, the \(J-H\) color for mid to late M-type objects is insensitive to spectral type (Leggett et al. 2002), so uncertainties in the spectral type of 2M2234+4041AB do not affect our determination of extinction.

The mean Two Micron All Sky Survey (2MASS) \(J-H\) color of M6 V objects from Dwarfarchives14 (Kirkpatrick et al. 1991, 1995; Kirkpatrick 1992) is 0.58 mag with a standard deviation of 0.07 mag. The 2MASS \(J-H\) color of 2M2234+4041AB is 0.74 ± 0.03 mag. Dereddening the \(J-H\) color of 2M2234+4041AB (0.74 ± 0.03) to the field M6 V color, using \((AV-A_H)/AV = 0.1\) (values from ADPS15), requires \(AV = 1.6 \pm 0.8\) mag. This may represent an upper limit on \(AV\), however, as young objects may have redder intrinsic colors than older field objects (Kirkpatrick et al. 2006). As a cross-check, we compiled 2MASS PSC photometry for 24 young M6 type objects in Upper Scorpius from Ardila et al. (2000) and Slesnick et al. (2006). At 5 Myr old, most of the gas and dust in the Upper Scorpius region have been dispersed by OB stars in the region. Thus Upper Scorpius objects should have very low dust extinction, and provide a good estimate of the intrinsic colors of young objects. The mean \(J-H\) color of the Upper Scorpius M6 objects is 0.69 mag, with a standard deviation of 0.07 mag, which implies \(AV = 0.5 \pm 0.8\) for 2M2234+4041AB, which is in agreement (to within the uncertainties) with the \(AV\) we derive from comparison with field dwarf colors. Based on the \(AV\)'s and uncertainties from dereddening the \(J-H\) color of 2M2234+4041AB to field and young M6 objects, we adopt an extinction value of \(AV = 1.1 \pm 1.1\) mag.

3.3. Age

3.3.1. Lithium

Lithium is destroyed at core temperatures of \(2-3 \times 10^6\) K. Such hot temperatures exist in the central regions of the lowest mass stars and high mass brown dwarfs (Chabrier et al. 1996). The timescale for lithium depletion is dependent on mass, with higher mass stars burning their lithium more quickly than lower mass stars. Figure 5 shows lithium detected in the spectrum of 2M2234+4041AB, with an equivalent width of 0.83 ± 0.02 Å (the mean of the values listed in Table 3). Staufier et al. (1998) found that Pleiades stars with spectral types earlier than M6.5 had depleted their lithium. Thus, for a spectral type of M6, the detection of lithium in 2M2234+4041AB places an upper limit on the age of \(\lesssim 100\) Myr, based on the age of Pleiades (Meynet et al. 1993).

3.3.2. L'-Band Excess

The detection of infrared emission in excess of that expected from the stellar photosphere is widely used as an indicator of circumstellar disks. Liu et al. (2003) found that objects with spectral types as late as M8 can exhibit excess emission in \(L'\) band. Figure 8 shows the \(K_S-L'\) colors for 2M2234+4041A and B compared to the colors of field dwarfs (Leggett et al. 2002; Reid & Cruz 2002; Leggett et al. 2003). The dereddened \(K_S-L'\) colors of 2M2234+4041A and B are 0.96 ± 0.06 mag and 0.78 ± 0.07 mag, whereas the average \(K_S-L'\) color of M5–M7 type field dwarfs is 0.45 mag. Thus, 2M2234+4041A and B have \(K_S-L'\) excesses detected at the 8 and 5σ levels, respectively, and likely possess circumstellar disks. Half of primordial disks around stars dissipate by an age of \(\sim 3\) Myr and all have dissipated by \(\sim 6\) Myr (Haisch et al. 2001). There is some evidence that primordial disks around brown dwarfs might be slightly longer lived than disks around stars (e.g., Riaz & Gizis 2008), so it is difficult to place an upper limit on the age of 2M2234+4041AB based solely on the presence of its circumstellar disk.

It is important to note that while the absolute value of \(K_S-L'\) for 2M2234+4041A and B has an uncertainty of 0.06–0.07 mag, the uncertainty in their relative \(K_S-L'\) colors is smaller (0.04 mag), so the difference in the \(K_S-L'\) colors of the two components is well detected (\(\Delta K_S-L' = 0.18 \pm 0.04\) mag). The presence of circumstellar disks in both components of a wide, low-mass binary system is interesting, as such systems are rare (e.g., Allers et al. 2007). Given that 2M2234+4041A and B have nearly identical spectral types and \(J, H, K_S\) brightnesses and are presumably coeval, the difference in their excess is particularly compelling, as it implies that the physical structures of their disks are different. Models of circumstellar disks (e.g., D’Alessio et al. 2006; Dullemond et al. 2001) indicate that differences in the radius of an inner

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14 http://www.dwarfarchives.org

15 The Asiago Database on Photometric Systems (ADPS) is available via http://ulisse.pd.astro.it/Astro/ADPS/.
disk hole, the height of the disk rim, the accretion rate, or the inclination of disk could explain the relative $K_S - L'$ colors of 2M2234+4041A and B. Unfortunately, with only $K_S - L'$ colors, we cannot distinguish between these scenarios.

### 3.3.3. Accretion Indicators

Young, low-mass objects often show spectroscopic signatures of accretion from circumstellar disks. Atomic hydrogen lines, specifically H$\alpha$ emission, are commonly used to measure accretion rates. Table 3 lists the H$\alpha$ equivalent widths (EWs) and 10% widths measured in our HIRES spectra of 2M2234+4041AB. White & Basri (2003) found that nonaccreting stars and brown dwarfs can have strong H$\alpha$ emission (EWs of $-3.0 \pm 0.3$ Å) and $-2.5 \pm 0.3$ Å) and calculate log($L_{\text{Br} \gamma}/L_\odot$) of $-5.20 \pm 0.04$ and $-5.82 \pm 0.05$ for 2M2234+4041A and B, respectively, assuming a distance of 325 ± 50 pc to 2M2234+4041AB (see Section 3.4). The uncertainties are determined from the formal errors of the Gaussian fit and do not include distance uncertainties. Using the relation between accretion luminosity and H$\alpha$ luminosity from Muzerolle et al. (1998), we calculate accretion luminosities, log($L_{\text{acc}}/L_\odot$), of $-2.1 \pm 1.3$ and $-2.3 \pm 1.3$ for 2M2234+4041A and B. Assuming a mass of 0.1 $M_\odot$ (Section 3.5) and a radius of 0.982 $R_\odot$ (appropriate for a 1 Myr old, 0.1 $M_\odot$ object; Baraffe et al. 1998), we calculate accretion rates (from $M_{\text{acc}} = L_{\text{acc}}/GM_{\odot}$) of $2.4 \times 10^{-9}$ $M_\odot$ yr$^{-1}$ for 2M2234+4041A and B, respectively. The accretion rates we measure from H$\alpha$ are larger than the accretion rate we calculate from H$\alpha$, but given the large uncertainties in the H$\alpha$ accretion luminosities and the distance to the source, this is not unexpected. The accretion rates we measure from H$\alpha$ and H$\alpha$ are consistent with values of $M$ for sources of similar mass (Muzerolle et al. 2005), and indicate that both components of 2M2234+4041AB are young and actively accreting.

### 3.3.4. Gravity Sensitive Spectral Features

To further constrain the age of 2M2234+4041AB we examine the gravity (age) sensitive absorption lines of K$\alpha$ and Na$\alpha$ (Allers et al. 2007; McGovern et al. 2004; Gorlova et al. 2003) in the SpeX J-band spectrum of 2M2234+4041AB. For comparison to the 2M2234+4041AB spectrum, we selected objects with ages determined by their membership in: the Taurus star-forming region ($\sim$1 Myr; Luhman et al. 2003a), the Upper Scorpius OB association ($\sim$5 Myr; Preibisch et al. 2002), the TW Hydra moving group ($\sim$10 Myr; Webb et al. 1999), and the general field dwarf population ($\sim$1 Gyr). We chose objects with optical spectral types of M6 (if available), so that we are comparing only the age sensitivity of spectral features. In Figure 3, we compare the SpeX spectrum of 2M2234+4041AB to SpeX spectra we obtained of CFHT-BD-Tau 18 (Taurus M6; Guieu et al. 2006), USco CTIO 75 (Upper Scorpius M6; Ardila et al. 2000), as well as a SpeX spectrum of TW A8B (TW Hydra M5; Webb et al. 1999) given to us by C. Deen (2007, private communication), and a spectrum of Gl406, a field M6 from Cushing et al. (2005). In Figure 3, one can clearly see the increase in K$\alpha$ and Na$\alpha$ line strengths with age. The line

![Figure 8. K$S - L'$ colors of 2M2234+4041A and B compared to field dwarfs.](image-url)
strengths in 2M2234+4041AB are noticeably weaker than the field, TW Hydra, and Upper Scorpius objects, indicating an age for 2M2234+4041AB of less than 5 Myr. The K I and Na I line strengths (and the entire spectrum) of 2M2234+4041AB are best matched by CFHT-BD-Tau 18, implying an age of \( \sim 1 \) Myr for 2M2234+4041AB. The K I 7700 Å line in the composite HIRES spectrum is also very weak and indicative of a young age (Shkolnik et al. 2009). Our resolved OSIRIS K-band composite HIRES spectrum is also very weak and indicative of a young age for 2M2234+4041AB. The field, TW Hydra, and Upper Scorpius objects, indicating an age of \( \sim 1 \) Myr for 2M2234+4041AB. The K I 7700 Å line in the composite HIRES spectrum is also very weak and indicative of a young age (Shkolnik et al. 2009). Our resolved OSIRIS K-band composite HIRES spectrum is also very weak and indicative of a young age for 2M2234+4041AB. Given its young age (\( \sim 1 \) Myr), null proper-motion measurement, and low RV (Table 4), where could 2M2234+4041AB have originated? 2M2234+4041AB lies 1.5 from the well-studied Herbig Ae/Be star, LkHα233 (Calvet & Cohen 1978), and near the young K-type stars, LkHα 230, 231, and 232, and the B star, HD 213976 (Figure 10). Based on the geometry and temperature derived from observations of molecular gas (CO, NH3, and H2CO) in the region, Olano et al. (1994) concluded that the LkHα stars likely formed from Condensation A of the LBN 437 complex, which is externally heated by HD 213976. HD 213976 has a Hipparcos measured parallax of 3.08 \( \pm \) 0.56 mas (van Leeuwen 2007), corresponding to a distance of 325 \( \pm \) 50 pc. If at this distance, the projected separation of 2M2234+4041AB is 51 \( \pm \) 17 AU.

One method of establishing membership with a group of stars is common space motion. The null proper motion we measure for 2M2234+4041AB is consistent with the Hipparcos measured proper motion of HD 213976 (\( -1.67 \pm 0.46, -3.06 \pm 0.45 \) mas yr\(^{-1} \)) (van Leeuwen 2007). The proper motions reported by Ducourant et al. (2005) for LkHα 230.
(4 ± 7, −11 ± 3 mas yr$^{-1}$), LkHα231 (−9 ± 5, −8 ± 5 mas yr$^{-1}$), and LkHα232 (−11 ± 5, −3 ± 5 mas yr$^{-1}$) are also low. Our measured RV of 2M2234+4041AB is −10.6 ± 0.5 km s$^{-1}$ (Table 4), which agrees with the RV of LkHα233 inferred from the relative velocities of its red and blue shifted jets (∼−10 km s$^{-1}$; Perrin & Graham 2007). The RV of HD 213976 (−17.2 km s$^{-1}$) agrees with that of 2M2234+4041AB to within the ∼10 km s$^{-1}$ spread observed for stars in the Taurus star-forming region (Bertout & Genova 2006). Kinematically, 2M2234+4041AB could be associated with the LkHα233 group.

The distance typically assumed for the LkHα233 group of young stars is 880 pc, a photometric distance of HD 213976 dating back to Herbig (1960). Photometric distances of 700 and 600 pc were found for LkHα231 and 232 (Calvet & Cohen 1978), and Chernyshev & Shevchenko (1988) determined a photometric distance of 600 pc for 21 emission stars in the region. Given the large discrepancy between the astrometric distance (325±72 pc) and the original photometric distance (880 pc) of HD 213976, it is worthwhile to re-examine the photometric distance to the LkHα233 group and see if the discrepancy can be resolved.

Calculating a photometric distance for LkHα233 is difficult due to the fact that its circumstellar disk is viewed edge-on, and thus LkHα233 is likely seen in scattered light (Perrin & Graham 2007). We can, however, obtain photometric distances for HD 213976, LkHα232 and LkHα231. Hernández et al. (2005) report an optical spectral type of B3 for HD 213976 and a low extinction (A$\alpha$ = 0.24 ± 0.12 mag). To obtain a photometric distance to HD 213976, we compare its brightness to B2–B4 type stars in Upper Scorpius. The mean absolute J-band brightnesses of twelve B2–B4 type Upper Scorpius members (Hernández et al. 2005) is −0.72 ± 0.73 mag (for d = 145 pc; de Zeeuw et al. 1999). By comparison to the brightness of Upper Scorpius objects, the 2MASS J-band magnitude of HD 213976 (7.19 ± 0.02 mag) implies a distance modulus of 7.91 mag and a distance of 382 ± 109 pc, in good agreement with the Hipparcos distance. Similarly, one can compare the brightnesses of LkHα232 and LkHα231 (SpTs of K3 and K4, respectively; Herbig & Bell 1988) to young Taurus objects of similar spectral type from Kenyon & Hartmann (1995). The mean absolute 2MASS J-band flux of K2–K5 type stars in Taurus (corrected for reddening using the published A$\alpha$ values of Kenyon & Hartmann 1995, and assuming a distance of 143 pc; Loinard et al. 2008) is 3.80 ± 1.17 mag. Objects similar to Taurus K2–K5 stars at 325 pc should then have observed J-band magnitudes of 11.35 ± 1.17, in good agreement with the 2MASS J-band photometry of LkHα232 and 231 (11.18 ± 0.03 and 11.74 ± 0.02 mag respectively). Our newly calculated photometric distances of HD 213976, LkHα232 and LkHα231 are in good agreement with the astrometric distance of 325±72 pc, which we adopt for the LkHα233 group and 2M2234+4041AB. This distance is similar to the distance of Lacerta OB1 (368 ± 17 pc de Zeeuw et al. 1999), which lies ∼5° (∼55 pc) away, and may indicate that the LkHα233 group is a site of recent star formation associated with Lac OB1.

3.5. Luminosity

To calculate the bolometric luminosities of 2M2234+4041A and B, we apply a bolometric correction (BC) to their extinction-corrected near-IR magnitudes. In theory, bolometric corrections can be made at any wavelength, but because 2M2234+4041A and B harbor circumstellar disks (Sections 3.3.2 and 3.3.3), we choose to apply a bolometric correction at J-band (BC$J$) to minimize possible contamination by circumstellar disk emission. To find an appropriate BC$J$, we tabulated 2MASS J-band magnitudes and m$_{bol}$ of field M5.5–M6.5 type dwarfs from Leggett et al. (2000). The mean BC$J$ is 2.00 mag with a standard deviation of 0.06 mag. For a distance of 325+72 −50 pc, and a solar M$_{bol}$ of 4.76 mag, we calculate luminosities (log(L$\star$/L$_{\odot}$)) of −0.27 ± 0.21 and −0.30 ± 0.21 dex for 2M2234+4041A and B, where the uncertainties were calculated from the uncertainties in A$\alpha$, distance, photometry, and BC$J$.

3.6. Mass

Masses (and ages) of low-mass stars and brown dwarfs can be determined from evolutionary models by placing them on an H-R diagram with the objects’ luminosities determined photometrically and effective temperatures determined spectroscopically. The spectral type of 2M2234+4041AB, M6 ± 1, corresponds to an effective temperature of 2900±150 K according to the SpT–T$_{eff}$ relationship appropriate for young objects of Luhman et al. (2003b). The top panel of Figure 11 shows the position of 2M2234+4041A on an H-R diagram with the evolutionary models of Baraffe et al. (1998) overlaid. 2M2234+4041A lies well above the 1 Myr old isochrone, making it difficult to estimate its mass using this method, though it is not uncommon for young objects to be overluminous relative to evolutionary models (e.g., Luhman 2004b).

Given the well established age of <5 Myr, we can estimate the mass of 2M2234+4041AB from evolutionary models using age and effective temperature. The bottom panel of Figure 11 shows the effective temperature and age range of 2M2234+4041AB, with iso-mass contours from Baraffe et al. (1998) overlaid. Fortunately, within the effective temperature range of 2M2234+4041AB, the iso-mass contours are nearly vertical, or age independent. At an age of 1–2 Myr, the T$_{eff}$ of 2M2234+4041AB is closest to the 0.100 M$_{\odot}$ iso-mass track, but masses of 0.060–0.175 M$_{\odot}$ are also within the range of uncertainty in effective temperature and age. Though the possible mass of 2M2234+4041AB falls in a wide range, it is the first potential VLM member of the LkHα233 group.

3.7. Orbital Period

We have measured the projected separation of 2M2234+4041AB to be 51±31 AU, but the semimajor axis of the binary depends on its orbital parameters. Following the method of Torres (1999), we assume random viewing angles and a uniform eccentricity distribution between 0 < e < 1 to derive a correction factor of 1.10±0.91 (68.3% confidence limits) for converting the projected separation into a semimajor axis. This results in a semimajor axis of 57±31 AU. For a total mass of 0.2 M$_{\odot}$, this corresponds to an orbital period of 1000±500 years. Unfortunately, the orbital period of 2M2234+4041AB is far too long for our observations to detect any significant relative motion of the binary.

3.8. Could 2M2234+4041AB be a Higher Order Multiple System?

As noted in Section 3.4 and shown in Figures 9 and 11, 2M2234+4041A is overluminous relative to young Taurus M6 objects and the theoretical 1 Myr old isochrone. A common explanation for overluminosity is unresolved multiplicity. Is it possible that 2M2234+4041AB is a higher order multiple
we determine a mass for 2M2234+4041A and B of 0.100 $M_\odot$.

The iso-mass contours at young ages are nearly vertical (age insensitive). Thus, the strength of the K is based on the presence of a circumstellar disk, evidence of accretion, and (Table 1). Our LGS AO observations, however, would only be evidence of additional companions in three epochs of imaging of 2M2234+4041A and B are nearly identical. We see no ev-

system? Both components would need to have similar companions (i.e., a quadruple system) since the magnitudes and colors of 2M2234+4041A and B are nearly identical. We see no evidence of additional companions in three epochs of imaging (Table 1). Our LGS AO observations, however, would only be able to detect companions with separations $\gtrsim$13 AU, whereas most field VLM binaries have tighter separations (Burgasser et al. 2007). Neither epoch of HIRES data show evidence of spectroscopic binarity, and the RV shows no sign of variation. Interferometric or higher spatial resolution observations of the source would be needed to definitively rule out a higher order multiple system.

3.9. Will 2M2234+4041AB be Disrupted?

The 51 AU projected separation of 2M2234+4041AB is significantly wider than those typical of field VLM binaries (3–15 AU; Burgasser et al. 2007), which may indicate that binary systems similar to 2M2234+4041AB are disrupted before they reach the age of the field population (a few Gyr). In recent years, a handful of young, very wide (>100 AU) binaries have been discovered (Béjar et al. 2008; Bouy et al. 2006; Close et al. 2007; Luhman 2004a). Close et al. (2007) suggest that such young, wide systems might become unbound due to dynamical interactions with other young stars in their natal clusters. The separation and total mass of 2M2234+4041AB, however, meet the stability criteria of Close et al. (2007), meaning that systems similar to 2M2234+4041AB are likely to survive the dispersion of their cluster and are unlikely to be disrupted by encounters with field stars. Even if the actual masses of 2M2234+4041A and B were at the low end of their possible mass range (0.06 $M_\odot$), the system would still be considered stable. The binding energy ($GM_1M_2/a$) of 2M2234+4041AB is $\sim$3.4 $\times$10$^{12}$ erg which is lower than all but two (out of 69) known field VLM binaries, indicating that systems similar to 2M2234+4041AB are rare, but possible among the field population.

4. CONCLUSIONS

As a part of our Keck LGS AO survey of young field objects, we discovered 2M2234+4041AB to be a binary. Over three epochs of imaging, the separation of the system does not change, indicating that 2M2234+4041A and B are physically associated (though the low proper motion of the system makes it difficult to confirm if the pair is actually comoving). The similarity in spectral shape and features as well as the fluxes and colors of 2M2234+4041A and B suggest that both components have the same mass, spectral type, and age. From composite optical and near-IR spectroscopy, we derive a spectral type of M6 for the system. Evidence of the youth of the system is the detection of $K_s - L'$ excesses for 2M2234+4041A and B (presumably due to the presence of circumstellar disks). The level of excess, however, differs for the two components, indicating that the physical structures of their disks must be different. The strengths of H$_\alpha$ and Br$_\gamma$ emission lines signify ongoing accretion, in agreement with the young ($\sim$1 Myr) age we derive for the system based on comparison of near-IR gravity sensitive spectral features with objects of similar spectral type and known age. By constraining the age and $T_{\text{eff}}$ (from its spectral type), we determine individual masses of 0.10$^{+0.075}_{-0.04} M_\odot$ for 2M2234+4041A and B by comparison to evolutionary models (Baraffe et al. 1998).

The original identification of 2M2234+4041AB was as a young, field object, not associated with any known star-forming regions (Cruz et al. 2003). However, 2M2234+4041AB lies 1.5 away from the well-studied HAeBe star, LkHα233. LkHα233 belongs to a small group of young stars (including LkHα232, 231, and HD 213976), historically thought to lie at a distance of 880 pc (the photometric distance to HD213976; Herbig 1960). Recently, van Leeuwen (2007) reported a Hipparcos parallax measurement of 3.08 ± 0.56 mas for HD 213976, corresponding to a distance of 325$^{+72}_{-50}$ pc. We re-examined the photometric distance to HD213976 as well as LkHα231 and 232. Using the absolute J-band magnitudes of young objects (Taurus or Upper Scorpius), we derive photometric distances that are in agreement with the astrometric distance of 325 pc. 2M2234+4041AB is the first potential VLM member of the group. At a distance of 325 pc, the physical separation of 2M2234+4041AB is 51 AU. It is interesting that the first VLM object discovered in the region happens to be a young, wide binary. The binding energy of 2M2234+4041AB, indicates that it is unlikely to be dynamically disrupted (Close et al. 2007).
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