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## DISCOVERY OF A CANDIDATE FOR THE COOLEST KNOWN BROWN DWARF\*

K. L. LUHMAN<sup>1,2</sup>, A. J. BURGASSER<sup>3,4</sup>, AND J. J. BOCHANSKI<sup>1</sup>

<sup>1</sup> Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA; [kluhman@astro.psu.edu](mailto:kluhman@astro.psu.edu)

<sup>2</sup> Center for Exoplanets and Habitable Worlds, The Pennsylvania State University, University Park, PA 16802, USA

<sup>3</sup> Center for Astrophysics and Space Science, University of California San Diego, La Jolla, CA 92093, USA

<sup>4</sup> Massachusetts Institute of Technology, Kavli Institute for Astrophysics and Space Research, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

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### ABSTRACT

We have used multi-epoch images from the Infrared Array Camera on board the *Spitzer Space Telescope* to search for substellar companions to stars in the solar neighborhood based on common proper motions. Through this work, we have discovered a faint companion to the white dwarf WD 0806-661. The comoving source has a projected separation of 130'', corresponding to 2500 AU at the distance of the primary (19.2 pc). If it is physically associated, then its absolute magnitude at 4.5  $\mu\text{m}$  is  $\sim 1$  mag fainter than the faintest known T dwarfs, making it a strong candidate for the coolest known brown dwarf. The combination of  $M_{4.5}$  and the age of the primary (1.5 Gyr) implies an effective temperature of  $\sim 300$  K and a mass of  $\sim 7 M_{\text{Jup}}$  according to theoretical evolutionary models. The white dwarf's progenitor likely had a mass of  $\sim 2 M_{\odot}$ , and thus could have been born with a circumstellar disk that was sufficiently massive to produce a companion with this mass. Therefore, the companion could be either a brown dwarf that formed like a binary star or a giant planet that was born within a disk and has been dynamically scattered to a larger orbit.

**Key words:** binaries: visual – brown dwarfs – infrared: planetary systems – planetary systems – planets and satellites: atmospheres

### 1. INTRODUCTION

The methane-bearing T dwarfs comprise the coolest known class of brown dwarfs (Burgasser et al. 2006, references therein). These sources have atmospheres that are sufficiently cool for H<sub>2</sub>O and CH<sub>4</sub> gases to form in abundance, resulting in distinct, planet-like spectra (Oppenheimer et al. 1995; Geballe et al. 1996). The similar masses and effective temperatures of T dwarfs as compared to “warm” exoplanets make them critical benchmarks for theoretical atmospheric and interior models of substellar objects (Marley et al. 1996; Allard et al. 1996). Although more than 200 T dwarfs have been discovered over the last decade, there remains a large gap in temperature between the coolest known T dwarfs ( $T_{\text{eff}} \sim 500$  K; Burningham et al. 2008; Delorme et al. 2008; Lucas et al. 2010) and the Jovian planets ( $T_{\text{eff}} \sim 150$  K). Based on theoretical spectra, objects in this temperature range may exhibit spectroscopic characteristics that are distinct from those of T dwarfs, including strong near-IR NH<sub>3</sub> absorption and scattering from water ice clouds (Burrows et al. 2003). These sources may therefore represent a new spectral class tentatively designated as Y dwarfs (Kirkpatrick et al. 1999, 2005). In addition, the coolest brown dwarfs encompass the oldest and lowest mass “stars” in the Galaxy, probing the history and efficiency of star formation at the planetary-mass limit.

Wide-field imaging surveys over the last decade have been successful in uncovering free-floating brown dwarfs at progressively cooler temperatures. However, the relatively low surface density of field brown dwarfs on the sky (Metchev et al. 2008) necessitates imaging of very large areas and spectroscopy of samples of candidates that can be highly contaminated. A survey for companions to stars in the solar neighborhood ( $d \lesssim 30$  pc) is an appealing alternative for identifying the coolest brown dwarfs

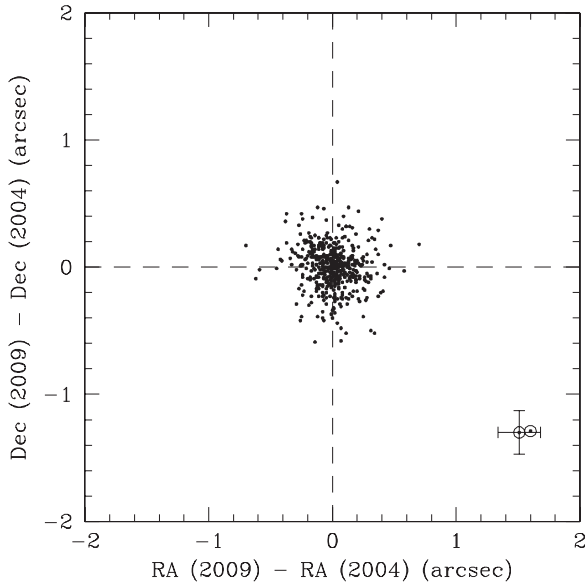
because of the smaller search volume that is required. In addition, the age, distance, and metallicity measured for a primary can be adopted for its companion, parameters which are usually difficult or impossible to measure for isolated brown dwarfs. Several of these benchmark T dwarfs, including the prototype Gliese 229B, have been discovered as companions to nearby main-sequence stars (Nakajima et al. 1995; Oppenheimer et al. 1995; Wilson et al. 2001; Burgasser et al. 2000, 2005, 2010; Scholz et al. 2003; McCaughrean et al. 2004; Biller et al. 2006; Mugrauer et al. 2006; Luhman et al. 2007; Burningham et al. 2009; Goldman et al. 2010; Scholz 2010) as well as a white dwarf (Day-Jones et al. 2011).

The Infrared Array Camera (IRAC; Fazio et al. 2004) on board the *Spitzer Space Telescope* (Werner et al. 2004) offers the best available sensitivity to cool companions in wide orbits ( $T_{\text{eff}} < 1000$  K,  $r > 100$  AU). We have used multi-epoch images from IRAC to search for substellar companions in the solar neighborhood based on common proper motions. In this Letter, we present the discovery of a new companion that is a candidate for the coolest and faintest known brown dwarf.

### 2. SPITZER DETECTION OF A FAINT COMPANION

To search for substellar companions around nearby stars, we have considered nearly all stars that have been observed with IRAC in multiple epochs and that should show detectable motions in these data ( $\gtrsim 0''.5$ , see Figure 1) based on their known proper motions. This sample consists of  $>600$  stars, brown dwarfs, and white dwarfs. The plate scale and field of view of IRAC are  $1''.2 \text{ pixel}^{-1}$  and  $5''.2 \times 5''.2$ , respectively. The camera produces images with  $\text{FWHM} = 1''.6\text{--}1''.9$  from 3.6 to 8.0  $\mu\text{m}$ . Among the four IRAC filters, we have analyzed the images collected at 3.6 and 4.5  $\mu\text{m}$  since they offer the best spatial resolution and sensitivity to cool brown dwarfs. Initial processing of the images was performed by the pipeline at the Spitzer Science Center and the resulting data were combined into the final images using R. Gutermuth's

\* Based on observations made with the *Spitzer Space Telescope*, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA, and with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile.

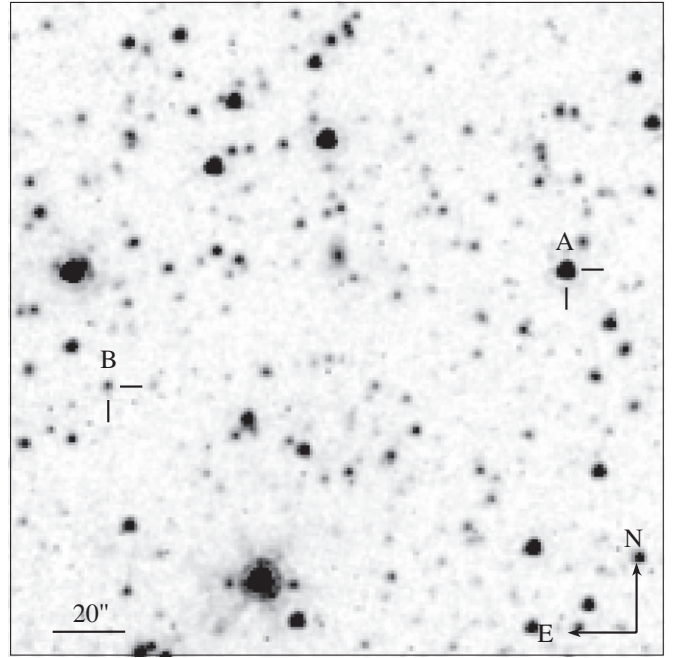


**Figure 1.** Differences in coordinates of sources near WD 0806-661 between two epochs of IRAC images at  $4.5 \mu\text{m}$  (points). We have circled WD 0806-661 and a new companion that shows the same motion. We also include  $1\sigma$  error bars for the latter.

WCSmosaic IDL package (Gutermuth et al. 2008). Pipeline versions S18.7.0 and S18.12.0 were used for the data discussed in this Letter.

For each nearby star, we used the task *starfind* within IRAF to measure positions for all point sources in the images from the multiple epochs. We converted the pixel coordinates to equatorial coordinates using the World Coordinate Systems produced by the pipeline and matched the source lists between the epochs. We then measured a new World Coordinate System for the first epoch image using the pixel coordinates from the first epoch and the equatorial coordinates from the second epoch, which enabled more accurate relative astrometry between the two epochs. To identify possible companions, we checked for sources with motions that were consistent with the motions measured for the primaries from these data. If accurate positions were unavailable for the primary because of saturation in the IRAC data, we instead computed the motion expected for the primary based on its published proper motion and the elapsed time between the two epochs.

We have identified a new companion to the DQ white dwarf WD 0806-661 (L97-3), which we refer to as WD 0806-661 B. The primary was observed by IRAC on 2004 December 15 and 2009 August 24 through programs 2313 (M. Kuchner) and 60161 (M. Burleigh) with total exposure times of 134 and 536 s, respectively. The companion has a projected separation of  $130''$ , corresponding to 2500 AU at the distance of the white dwarf (19.2 pc; Subasavage et al. 2009). The motion of WD 0806-661 B between the two epochs of IRAC data agrees closely with that of the primary and is significantly greater than the zero motion expected for a background source. This is demonstrated in Figure 1, which shows the differences in equatorial coordinates between the two epochs for all stars with photometric errors less than 0.1 mag in the second epoch. For stars that have fluxes within  $\pm 0.5$  mag of WD 0806-661 B, the standard deviations of the differences in right ascension and declination in Figure 1 are  $0''.17$ , whereas WD 0806-661 B exhibits a motion of  $2''$ . The astrometric accuracy for the primary is higher since it is 3 mag brighter than WD 0806-661 B.



**Figure 2.** IRAC  $4.5 \mu\text{m}$  image of WD 0806-661 A and B ( $3' \times 3'$ ).

**Table 1**  
Properties of WD 0806-661 A and B

Parameter	Value
WD 0806-661 A <sup>a</sup>	
Distance	$19.2 \pm 0.6$ pc
$\mu_\alpha$	$+340.3 \pm 1.8$ mas yr <sup>-1</sup>
$\mu_\delta$	$-289.6 \pm 1.8$ mas yr <sup>-1</sup>
Mass	$0.62 \pm 0.03 M_\odot$
Progenitor mass	$2.1 \pm 0.3 M_\odot$
Age	$1.5^{+0.5}_{-0.3}$ Gyr
WD 0806-661 B <sup>b</sup>	
Separation	$130.2 \pm 0''.2$ (2500 AU)
Position angle	$104^\circ.2 \pm 0^\circ.2$
$J$	$> 20$ mag
[4.5]	$16.75 \pm 0.05$ mag
Estimated $T_{\text{eff}}$	$\sim 300$ K
Estimated mass	$\sim 7 M_{\text{Jup}}$

**Notes.**

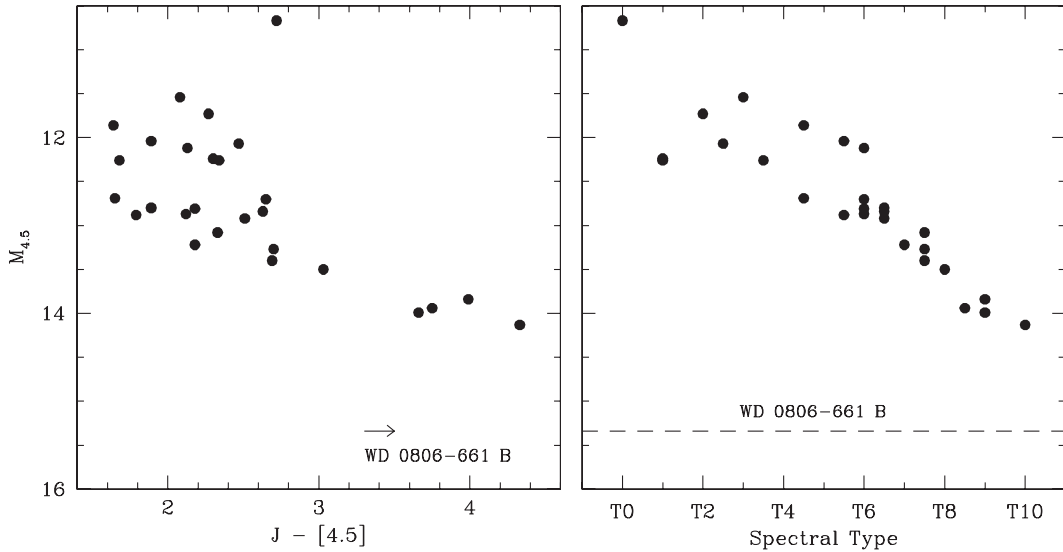
<sup>a</sup> Distance,  $\mu$ , and mass of the primary are from Subasavage et al. (2009). The progenitor mass and total age are estimated in Section 4.

<sup>b</sup> This work.

We measured photometry at  $4.5 \mu\text{m}$  for WD 0806-661 B with the methods described by Luhman et al. (2010). We present the astrometry and photometry for this object as well as other properties of the system in Table 1. The  $4.5 \mu\text{m}$  image of WD 0806-661 A and B from the second epoch is shown in Figure 2.

### 3. COLOR CONSTRAINTS

To investigate the nature of WD 0806-661 B, we have examined the available constraints on its colors. It was not observed at  $3.6$  or  $5.8 \mu\text{m}$  by IRAC in either epoch. It was encompassed by the  $8.0 \mu\text{m}$  images from the first epoch but was not detected. The resulting limit of  $[8.0] > 15$  implies  $[4.5] - [8.0] < 1.7$ , which is consistent with a stellar object at



**Figure 3.**  $M_{4.5}$  vs.  $J - [4.5]$  and  $M_{4.5}$  vs. spectral type for WD 0806-661 B (arrow and dashed line) and T dwarfs with measured distances and IRAC photometry (filled circles; Lucas et al. 2010; Leggett et al. 2010, and references therein).

any spectral type, including a T dwarf (Patten et al. 2006). We have not found any detections or useful flux limits for this object in any publicly available images.

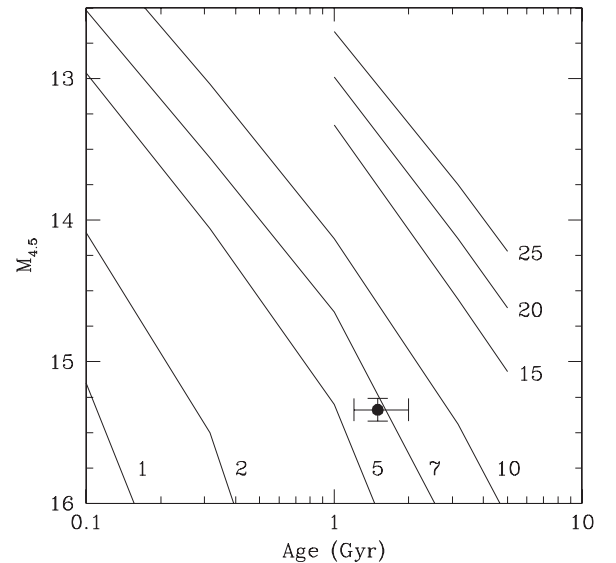
On 2010 December 23, we sought to obtain a spectrum of WD 0806-661 B with the Folded-Port Infrared Echellette (FIRE; Simcoe et al. 2008) at the Magellan 6.5 m Baade Telescope. However, it was not detected in the  $J$ -band acquisition images, which had a total exposure time of 45 s. By flux calibrating these images with photometry of unsaturated sources from the Point Source Catalog of the Two Micron All Sky Survey (Skrutskie et al. 2006), we estimate a magnitude limit of  $J > 20$  for WD 0806-661 B. The combination of this limit with the IRAC measurement at  $4.5 \mu\text{m}$  indicates a color of  $J - [4.5] > 3.3$ , which is consistent with a spectral type of  $\gtrsim T8$  (Eisenhardt et al. 2010; Leggett et al. 2010). A substellar object is the only type of companion that could be as red and faint as WD 0806-661 B.

#### 4. PHYSICAL PROPERTIES

To estimate the physical properties of WD 0806-661 B, we begin by assuming that it has the distance of the primary and plotting the resulting absolute magnitude at  $4.5 \mu\text{m}$  versus  $J - [4.5]$  and spectral type in Figure 3. For comparison, we include T dwarfs that have measured distances and IRAC photometry. These data indicate that WD 0806-661 B should be the coolest and faintest brown dwarf identified to date by a fairly large margin. For perspective, the sequence of known T dwarfs spans 2.5 mag, while WD 0806-661 B is 1 mag fainter than the bottom of that sequence.

As a likely companion, WD 0806-661 B should have the same age as its primary. By combining the mass of  $0.62 \pm 0.03 M_{\odot}$  for WD 0806-661 (Subasavage et al. 2009) with initial-final mass relations for white dwarfs (Kalirai et al. 2008; Williams et al. 2009), we compute a mass of  $2.1 \pm 0.3 M_{\odot}$  for the progenitor. A star born with this mass should have a main-sequence lifetime of  $810^{+450}_{-240}$  Myr (Iben & Laughlin 1989). The sum of that lifetime and the cooling age of  $670 \pm 40$  Myr from Subasavage et al. (2009) produces a total age of  $1.5^{+0.5}_{-0.3}$  Gyr.

We can estimate the mass and temperature of WD 0806-661 B by comparing its photometry to the fluxes predicted by theoretical evolutionary models. In Figure 4, we plot it on a



**Figure 4.**  $M_{4.5}$  vs. age for WD 0806-661 B if the distance and age of the primary are adopted (filled circle). For comparison, we include the magnitudes predicted by the theoretical spectra and evolutionary models from Burrows et al. (2003) for constant values of mass, which are labeled in units of  $M_{\text{Jup}}$  (solid lines).

diagram of  $M_{4.5}$  versus age under the assumption that it has the age and distance of the primary. Burrows et al. (1997, 2003) used their model interiors and atmospheres to compute effective temperatures, bolometric luminosities, and spectra for cool brown dwarfs across a range of masses and ages. We have convolved those synthetic spectra with the system throughput for the  $4.5 \mu\text{m}$  IRAC filter. The resulting magnitudes are plotted at constant values of mass in Figure 4. They indicate that WD 0806-661 B should have a mass of  $\sim 7 M_{\text{Jup}}$ . The models that best match the absolute magnitude and age of WD 0806-661 B have effective temperatures of  $\sim 300$  K.

#### 5. DISCUSSION

WD 0806-661 B is a strong contender for the faintest known brown dwarf based on the available photometric and astrometric measurements. With an estimated  $T_{\text{eff}} \sim 300$  K, it would be

significantly cooler than the latest T dwarf currently known ( $T_{\text{eff}} \sim 500$  K; Lucas et al. 2010). Moreover, its photosphere would be sufficiently cool to harbor water ice clouds, making it a likely prototype for the Y dwarf spectral class. We also estimate a mass of  $\sim 7 M_{\text{Jup}}$  for WD 0806-661 B from the evolutionary models. Given that cloud core fragmentation appears capable of making binary companions near this mass (e.g., Todorov et al. 2010), it seems likely that a companion of this kind in a very large orbit (2500 AU) would have formed in this manner. However, the mass estimate also falls within the range of masses measured for close-in extrasolar planets ( $\lesssim 15 M_{\text{Jup}}$ ; Marcy et al. 2005; Udry et al. 2007). Because the progenitor of the primary was fairly massive ( $\sim 2 M_{\odot}$ ), its circumstellar disk at birth could have been massive enough to give rise to a companion at this mass. Thus, WD 0806-661 B could be a giant planet that has been dynamically scattered to a larger orbit.

Spectroscopy and multi-band photometry are necessary to verify the substellar nature of WD 0806-661 B and to better estimate its physical properties. If confirmed as the coolest known brown dwarf, it will represent a valuable laboratory for studying atmospheres in a new temperature regime, and its colors will help to guide searches for the coldest brown dwarfs with facilities such as the Wide-field Infrared Survey Explorer and the *James Webb Space Telescope*.

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