NEW EXTINCTION AND MASS ESTIMATES FROM OPTICAL PHOTOMETRY OF THE VERY LOW MASS BROWN DWARF COMPANION CT CHAMAeleon TIS B WITH THE MAGELLAN AO SYSTEM

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ABSTRACT

We used the Magellan adaptive optics system and its VisAO CCD camera to image the young low mass brown dwarf companion CT Chamaeleontis B for the first time at visible wavelengths. We detect it at r′, i′, z′, and Y5. With our new photometry and $T_{\text{eff}} \sim 2500$ K derived from the shape of its K-band spectrum, we find that CT Cha B has $A_V = 3.4 \pm 1.1$ mag, and a mass of $14 - 24 M_J$ according to the DUSTY evolutionary tracks and its 1–5 Myr age. The overluminosity of our r′ detection indicates that the companion has significant Hα emission and a mass accretion rate $\sim 6 \times 10^{-10} M_\odot \text{yr}^{-1}$, similar to some substellar companions. Proper motion analysis shows that another point source within 2″ of CT Cha A is not physical. This paper demonstrates how visible wavelength adaptive optics photometry (r′, i′, z′, Y5) allows for a better estimate of extinction, luminosity, and mass accretion rate of young substellar companions.

Key words: brown dwarfs – instrumentation: adaptive optics – planetary systems – planets and satellites: individual (CT Cha B) – stars: individual (CT Cha) – stars: pre-main sequence

1. INTRODUCTION

As more and more brown dwarfs and planetary companions are being discovered, characterizing them in the visible regime yields a more complete picture of the spectral energy distribution (SED) and more insight into physical properties as well as formation scenarios. For instance, a better estimate of extinction helps to derive bolometric luminosity and mass—especially for young objects ($\lesssim 10$ Myr) which may still have primeval dust and gas around them and suffer significant obscuration. However, extinction is problematic to measure because most of the high-contrast adaptive optics (AO) observations are done in the near-infrared, which is $\sim 10$ times less sensitive to dust at $K$ versus $V$. One simple treatment is to assume that the companion has the same amount of extinction as its host star (Patience et al. 2012), since in the early stages of star formation the binary might be embedded in a common envelope. For more evolved, fragmented systems both components may have their own disks, so this assumption might be invalid. Ideally one would like to acquire visible spectra or at least broad-band visible photometry to supplement near-IR measurements because visible wavelengths are a better probe for dust extinction. Yet high contrast optical observations on companions are very rare due to decreased contrast (Males et al. 2014) and the difficulty of correcting atmospheric turbulence at visible (defined here as $\lambda < 1 \mu m$) wavelengths. We therefore need an advanced AO system which can work in the visible to suppress the halo.

Here we present the first optical AO photometry of the CT Chamaeleontis system with the Magellan adaptive optics (MagAO) system, a powerful new 585-element AO system commissioned on the 6.5 m Clay Telescope (Close et al. 2013, 2014; Follette et al. 2013; Wu et al. 2013; Males et al. 2014). CT Cha A, a K7 classical T Tauri star (Weintraub 1990; Gauvin & Strom 1992), is located in the Chamaeleon I star-forming region. This region is close ($\sim 160$ pc) Whittet et al. 1997; Bertout et al. 1999; Luhman 2008) and as young (median age $\sim 2$ Myr: Luhman 2004) as the Taurus star-forming region and IC 348. It also has relatively low extinction (typical $A_V \lesssim 5$ mag; Cambrésy et al. 1997), enabling a clear view of young stars. The companion CT Cha B at 2′′ (430 AU) projected separation was discovered by Schmidt et al. (2008) in their Very Large Telescope (VLT) NACO survey. Based on its near-IR spectrum, the companion was estimated to be an M8-to-L0 ($T_{\text{eff}} \sim 2600 K$) low mass ($\sim 17 M_J$) brown dwarf with $A_V \sim 5.2$ mag. Schmidt et al. (2008) also imaged another closer object termed "cc2," whose true nature has remained puzzling (Schmidt et al. 2009; Robbeto et al. 2012). In this paper we present new visible AO observations providing a better measurement of $A_V$ and of the mass of CT Cha B. Our accurate astrometry allows us to determine that cc2 is, in fact, a background source.

2. OBSERVATIONS AND REDUCTION

MagAO observations with its VisAO camera (Close et al. 2013; Males et al. 2014) at r′ (0.62 μm), i′ (0.77 μm), z′ (0.91 μm), and Y5 (0.98 μm) were performed on 2013 April 6 (UT) during the second commissioning run. Seeing was stable, ranging from 0′′6 to 0′′8. We locked the AO system on CT Cha A (R = 12 mag) at 100 modes and 625 Hz.7 The achieved FWHMs were 0′′1, 0′′08, 0′′06, 0′′06 for r′, i′, z′, Y5, respectively. Strehl ratios were low due to only correcting 100 modes, since the guide star was somewhat faint for VisAO. We obtained saturated images to boost signal-to-noise ratio (S/N), with unsaturated data sets for relative photometry (top row in Figure 1). As a young accreting star, CT Cha A varies its brightness by

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7 The faintness of this guide star prevented us from using all 378 modes at 1000 Hz which typically requires $R \lesssim 10$ mag guide stars.
et al. 1998; Ghez et al. 1997; Law et al. 1996). In order to
bottom row in Figure 1) without any loss of flux from self-
original images to further bring out any faint point source object
subtraction. Anisoplanatic effects are still small at this small
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and PSF fitting photometry on CT Cha B. Uncertainties of B are
saturated data set before any halo subtraction. Bottom row: primary’s halo removed by subtracting a rotationally symmetric point spread function (PSF). The
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Figure 2. Seven-year relative astrometry for CT Cha B (top) and cc2 (bottom). Proper motion of CT Cha A ($\mu_\alpha \cos \delta = -21.3$ mas yr$^{-1}$, $\mu_\delta = 6.3$ mas yr$^{-1}$) is from Schmidt et al. (2008). The ellipse in dashed line shows the convolution between the orbital motion and astrometric uncertainty. Apparently cc2 is not a bounded nor a non-moving background object. It is, in fact, a background star moving northwestward at $\sim 15.4$ mas yr$^{-1}$ ($\mu_\alpha \cos \delta \sim -8.2$ mas yr$^{-1}$ and $\mu_\delta \sim 13.0$ mas yr$^{-1}$; absolute proper motion). For CT Cha B, the MagAO value is consistent with those measured from archive NACO images, showing that it is a physical companion.

Table 2
MagAO Astrometry on 2013 April 6 (UT)

| Filter | Plate Scale (" pixel$^{-1}$) | Name | Separation (") | P.A. (") |
|--------|-----------------------------|------|----------------|---------|
| $r'$   | 0.007917 ± 0.000015         | B    | 2.717 ± 0.030  | 298.8 ± 0.6 |
| $i'$   | 0.007907 ± 0.000015         | cc2  | 1.962 ± 0.004  | 69.8 ± 0.3  |
| $z'$   | 0.007911 ± 0.000012         | B    | 2.679 ± 0.004  | 69.7 ± 0.3  |
| $Y_S$  | 0.007906 ± 0.000014         | cc2  | 1.995 ± 0.003  | 69.7 ± 0.3  |

$HST$ narrow-band optical observations (Robberto et al. 2012). Judging from its color, cc2 is relatively blue ($r' - i' = 0.9$) so unlikely to be another low-mass companion. Robberto et al. (2012) also speculated that a faint “object” seen at [O I] $\lambda 1.5$ to the south of CT Cha A could be real, but we cannot confirm any other faint object in our images, especially at $r'$ where a narrow band [O I] or $H\alpha$ source might have been visible. Thus, it is unlikely to be a real object.

3.2. Astrometry

The nature of cc2 is not fully settled in the literature. Schmidt et al. (2009) presented two-year astrometry, showing that it is likely to be a background star. But Robberto et al. (2012) suggested that cc2 may be physically associated based on their single epoch $HST$ observations. We measured the positions of cc2 and CT Cha B in images taken by various instruments over $\sim 7$ yr time span (Figure 2). Significant common-proper motion has been found for CT Cha B, confirming it is physically bound. However, we detected a significant non-common $\sim 15.4$ mas yr$^{-1}$ northwestward motion for cc2, unambiguously demonstrating that it is not a co-moving companion but instead a background star, and not a member of Chamaeleon I.
3.3. SED Fitting and Derived Properties

3.3.1. Effective Temperature

To further narrow down the uncertainty of \(T_{\text{eff}}\), we retrieved the spectrum taken with the VLT SINFONI spectrograph (Schmidt et al. 2008), and calculated the \(\text{H}_2\text{O}-\text{K}_2\) index following the prescription of Rojas-Ayala et al. (2012). Assuming solar metallicity, we found that for CT Cha B this index is almost independent of extinction, ranging from 0.65 to 0.66 for \(A_V = 0\) to 5.5 mag. In Figure 3, we plotted the variation of the index with a range of surface gravity for 2000–2800 K BT-Settl atmospheric models (Allard et al. 2011). Within this temperature range, the \(\text{H}_2\text{O}-\text{K}_2\) index is rather insensitive to \(\log g\). Hence we are free to use it for young cool objects like CT Cha B. Our best fit to the index corresponds to a spectral type M9 ± 1 with \(T_{\text{eff}} = 2500 ± 100 \text{ K}\).

3.3.2. Extinction, Bolometric Luminosity, and Mass

CT Cha B was previously estimated from near-IR spectroscopy to have an extinction higher than its host star \((A_V = 5.2 \text{ mag versus } 1.3 \text{ mag}; \text{ Schmidt et al. 2008})\). Our data benefit from the fact that visible wavelengths are more sensitive to dust extinction, so we can determine \(A_V\) at higher precision with MagAO’s VisAO camera.

We applied multiple values of \(A_V\) following the extinction law in Fitzpatrick (1999) to redden the 2500 K BT-Settl synthetic spectra normalized at \(K_S\) (Figure 4). Minimization of the reduced \(\chi^2\) is based on the reddened models fit to the observed \(i', z', Y_S, J, \text{ and } H\) photometry (black points in Figure 5). We found that while the result is independent of surface gravity, \(\chi^2\) remains high even after including the ±0.3 mag uncertainty at \(K_S\). Some systematic errors may come into play. For example, the adopted extinction law might be invalid due to grain growth in the disk, or there could be multiple dust components. On the other hand, scattered light from the disk or outflow gas may contribute to our \(i'\) photometry, as in the case of R Mon (Close et al. 1997). In this picture, blue light follows indirect paths to the observer, avoiding passing through the disk and making our extinction estimate likely a lower limit. Another possible cause for higher \(\chi^2\) is that an overall offset ~0.5 mag might exist between the visible and near-IR data because they were taken on different nights and CT Cha A is a well-known variable. Finally, the companion itself could also be variable in the visible just like the primary due to accretion. In any case, with no prior knowledge of the material around CT Cha B, our current data yield a best fit to a lower extinction \(A_V = 3.4 ± 1.1 \text{ mag}\). We plotted the reddened synthetic spectrum together with the observed photometry in Figure 5.
We followed the approach in Hillenbrand (1997) to calculate the bolometric luminosity. We converted our $i'$ photometry to Cousins $I_C$, de-reddened it by $A_V = 3.4$ mag, applied the bolometric correction from Tinney et al. (1993) and Bessell (1995), and obtained log($L_{bol}/L_{\odot}$) = $-2.68 \pm 0.25$. As a comparison, we also calculated $L_{bol}$ from the $K$ flux following Close et al. (2007) and had a similar value log($L_{bol}/L_{\odot}$) = $-2.71 \pm 0.20$. Both values are consistent with log($L_{bol}/L_{\odot}$) = $-2.68 \pm 0.21$ in Schmidt et al. (2008). We also calculated CT Cha B’s radius using $L \propto R^2 T^4$ and obtained $\sim 2.4 R_J$. Then we applied the DUSTY evolutionary tracks (Chabrier et al. 2000; Baraffe et al. 2001) to derive a mass estimate of $\sim 14–24 M_J$ based on the $\sim 1–5$ Myr age and $T_{eff}$ (Figure 6). Therefore, CT Cha B is most likely a very low mass brown dwarf, just above the planetary mass limit.

3.3.3. Accretion Rate

Pa-β emission, an accretion signature, has been seen in CT Cha B’s $J$-band spectrum (Schmidt et al. 2008). Since CT Cha B is widely separated from the host star, it may harbor its own disk and still be actively accreting at this time. Figure 5 shows that our $r'$ detection is about 20 times brighter than its predicted continuum. This significant $r'$ excess seems to imply strong Hα emission from accretion, allowing us to calculate the mass accretion rate. Attributing $>95\%$ of the $r'$ flux to Hα and following the prescription of Close et al. (2014), we estimated $\dot{M} \sim 6 \times 10^{-10} M_{\odot}$ yr$^{-1}$, which is reasonable as it implies that a few $M_J$ of brown dwarf mass could be accreted in a few million years at the end of the gas-rich disk phase. The accretion rate we derived is also consistent with recent HST observations by Zhou et al. (2014), who measured $M \sim 10^{-11}–10^{-9} M_{\odot}$ yr$^{-1}$.
for three substellar companions GSC 6214-210 B, GQ Lup B, and DH Tau b based on their optical excess.

3.4. Implications

The different extinction between the primary and the secondary may imply that both objects have their own disks likely with different inclination angles, resembling conceptually the configuration of HK Tau A and B (Jensen & Akeson 2014). CT Cha B’s $r'$ excess, together with other accreting objects in Zhou et al. (2014), suggest that accretion disks could be common among young low-mass companions and favor the “star-like” formation via gravitational collapse and fragmentation of molecular clouds. The survival of these significant disks also implies that substellar companions form near their current locations rather than being ejected there (Kraus et al. 2014). Strategic Hα surveys such as MagAO’s ongoing Giant Accreting Proto-planets Survey (GAPplanetS) may have the potential to probe $\sim 1 M_J$ accreting giant planets and shed light on the earliest stage of planet formation (Close et al. 2014).

4. SUMMARY

MagAO observations on CT Cha at $r'$, $i'$, $z'$, and $Y_S$ have improved the accuracy of the extinction toward CT Cha B. The companion is detected in all of our optical filters, whereas no detections were made by HST. It is over-luminous at $r'$, indicating active accretion at a rate of $\dot{M} \sim 6 \times 10^{-10} M_{\odot}$ yr$^{-1}$. The $H_2O$-K2 index derived from the $K_S$ spectrum is consistent with a $T_{\text{eff}} = 2400$–2600 K brown dwarf. Using the BT-Settl model, we show that CT Cha B is best fit by $A_V = 3.4 \pm 1.1$ mag, which is lower than previous estimates and translates to a mass estimate of $14$–$24 M_J$ based on the DUSTY tracks. We do not see the faint southern [O I] source seen in previous HST observations, so it is unlikely to be real. Finally, our astrometry on cc2 is incompatible with a previous claim that it is a co-moving object.

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