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DEEP z-BAND OBSERVATIONS OF THE COOLEST Y DWARF*

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ABSTRACT

WISE J085510.83-071442.5 (hereafter, WISE 0855-07) is the coolest Y dwarf known to date and is located at a distance of 2.31 ± 0.08 pc, giving it the fourth largest parallax of any known star or brown dwarf system. We report deep z-band observations of WISE 0855-07 using FORS2 on UT1/Very Large Telescope. We do not detect any counterpart to WISE 0855-07 in our z-band images and estimate a brightness upper limit of AB mag > 24.8 ($F_\nu < 0.45\ \mu$Jy) at 910 $\pm$ 65 nm with 3σ confidence. We combine our z-band upper limit with previous near- and mid-infrared photometry to place constraints on the atmospheric properties of WISE 0855-07 via comparison to models which implement water clouds in the atmospheres of $T_{\rm eff} < 300$ K substellar objects. We find that none of the available models that implement water clouds can completely reproduce the observed spectral energy distribution of WISE 0855-07. Every model significantly disagrees with the (3.6 μm/4.5 μm) flux ratio and at least one other bandpass. Since methane is predicted to be the dominant absorber at 3–4 μm, these mismatches might point to an incorrect or incomplete treatment of methane in current models. We conclude that (a) WISE0855-07 has $T_{\rm eff} \sim$ 200–250 K, (b) $<$ 80% of its surface is covered by clouds, and (c) deeper observations, and improved models of substellar evolution, atmospheres, clouds, and opacities will be necessary to better characterize this object.

Key words: brown dwarfs – stars: individual (WISE J085510.83-071442.5) – stars: low-mass

Online-only material: color figures

1. INTRODUCTION

Y dwarfs are substellar objects located at the coolest and lowest-mass edge of the brown dwarf M–L–T–Y spectral sequence (Kirkpatrick et al. 2012 and references therein). Previous studies of Y0-1 spectral type objects reveal effective temperatures of 400–500 K and masses of 10–30 $M_{\rm Jup}$ (e.g., Cushing et al. 2011; Dupuy & Kraus 2013; Leggett et al. 2013). Models predict a distinct atmospheric chemistry for Y dwarfs: NH_3 becomes apparent in the near-infrared and various species condense to form clouds (Burrows et al. 2003). In the warmest Y dwarfs, these clouds are composed of Na_2S (Morley et al. 2012), but at temperatures lower than 300 K the clouds may include H_2O, NH_3, and other, more exotic species (Burrows et al. 2003; Visscher et al. 2006; Morley et al. 2014).

Most recently, Luhman (2014) announced the detection of WISE J085510.83-071442.5 (hereafter, WISE 0855-07), a Y dwarf with $T_{\rm eff} =$ 235–260 K at a distance of 2.31 ± 0.08 pc (Luhman & Esplin 2014), making it the fourth closest known stellar or brown dwarf system. WISE 0855-07 is the coolest Y dwarf known to date. Occupying a temperature regime intermediate between hotter and more massive L and T dwarfs ($T_{\rm eff} > 550$ K) and Jupiter ($T_{\rm eff} = 126$ K; e.g., Li et al. 2012), WISE 0855-07 provides a unique opportunity to test the presence of water clouds in the atmospheres of Y dwarfs at temperatures below 400 K.

Luhman (2014) and Wright et al. (2014) report observations of WISE 0855-07 from *WISE* (Wright et al. 2010), *Spitzer*, and ground-based facilities. However, the object is only detected by *WISE* and *Spitzer* in essentially two bandpasses at 3.6 μm and 4.5 μm. Beamín et al. (2014) also report a non-detection at Y band giving an upper limit of $Y > 24.4$ mag at the 3σ level. On the other hand, Faherty et al. (2014) announce a 2.6σ detection of WISE 0855-07 giving $J3 = 24.8^{+0.53}_{-0.35}$($J_{\rm MKO} = 25.0^{+0.53}_{-0.35}$), or equivalently an upper limit of $J3 > 23.8$ mag ($J_{\rm MKO} > 24.0$ mag) at 5σ. Faherty et al. compare these observations with chemical equilibrium atmospheric models and demonstrate that WISE 0855-07 is 2.7σ from cloudless atmosphere models and can be reproduced by partly cloudy models (50%) containing sulfide and water ice clouds. However, the latter have been disputed by Luhman & Esplin (2014) who find that the spectral energy distribution (SED) of WISE 0855-07 can be explained by cloudless models that implement non-equilibrium chemistry. Nevertheless, we show that none of the available models that implement water clouds match all the existing observations completely (see Section 3), emphasizing that theoretical predictions for Y-dwarf atmospheres are still quite uncertain. Obtaining a complete SED for WISE 0855-07 is essential for understanding atmospheric properties in the temperature regime below 400 K. In this paper, we present deep z-band observations of WISE 0855-07, determine its upper-brightness limit from our non-detection and discuss how our result constrains this object's atmospheric properties.

* Based on observations made with ESO Telescopes at the La Silla Paranal Observatory under program 293.C-5008(A).
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2. OBSERVATIONS AND DATA ANALYSIS

Observations of WISE 0855-07 were carried out on 2014 May 31 using FORS2 mounted on the Very Large Telescope (VLT)/UT1 at the ESO/Paranal observatory in Chile. FORS2 is a visual and near-UV focal reducer and low-dispersion spectrograph (Appenzeller et al. 1998). Observation were obtained in imaging mode using the red-optimized CCD through the z_GUNN+78 filter (λ_0 = 910 nm, FWHM = 130.5 nm) with the high-resolution collimator that gives a field of view of 4$'$.2 × 4$'$.2. Pixels were binned (2 × 2) resulting in a pixel scale of 0$''$.125 pixel^{-1}. In total, six images with an exposure time of 480 s each were taken. The telescope was pointed so that the predicted position of WISE 0855-07 was located on the upper chip of FORS2 which has a better sensitivity. A small telescope offset was applied after each integration, to avoid bad pixels and cosmic ray contamination.

All six frames were reduced in the standard manner using IRAF[11] (Tody 1993)—bias subtraction, flat-fielding, fringe correction and sky subtraction. The reduced frames were aligned and co-added, in order to obtain a higher signal to noise. Astrometry and photometry from the Pan-STARRS1 (PS1) catalog (Schlafly et al. 2012; Tonry et al. 2012; Magnier et al. 2013) were used to measure the world coordinate system and to provide flux calibrations for the combined image. We used the method of Finkbeiner et al. (2014) to transform $z_{\rm PS1}$ to the standard $z_{\rm SDSS}$. Due to the lack of standard stars with z_GUNN+78 measurements, we cannot apply a proper transformation between z_GUNN+78 and $z_{\rm SDSS}$ magnitudes. However, we apply the filter responses of the z_GUNN+78[12] and $z_{\rm SDSS}$ filters to theoretical spectra (Burrows et al. 2003; Morley et al. 2014, see Section 3) and find that the resulting flux varies at most ±0.05 mag from filter to filter. Hence, the uncertainty in the magnitude system cannot account for the differences between the observed data and the models (see Section 3).

We used IRAF/DAOFIND to search for a counterpart to WISE 0855-07. DAOFIND approximates a stellar point-spread function with an elliptical Gaussian function. DAOFIND identifies no counterpart to WISE 0855-07 at its expected position in our z-band frames (Figure 1). To place an upper limit on the z-band magnitude of the brown dwarf, we estimate the sky brightness and the sky standard deviation at this expected position. Using the calibrated photometry from PS1, we estimate an upper brightness limit for WISE 0855-07 of z_{AB} > 24.8 mag, or $F_\nu < 0.45\,\mu$Jy with 3σ confidence (corresponding to a direct measurement and uncertainty of 0.06 ± 0.13 μJy). This result is consistent with the non-detection of WISE 0855-07 in the Y-band using HAWK-I on UT4/VLT at the Paranal observatory by Beamín et al. (2014) and 2.6σ detection in J band by Faherty et al. (2014).

3. COMPARISON WITH MODELS AND DISCUSSION

We compare the ensemble of observations of WISE 0855-07 to atmospheric spectral models of cool substellar objects. We considered the full set of model spectra from Morley et al. (2014) and Burrows et al. (2003), both of which extend well below 300 K and include the effects of water clouds. Figures 2 and 3 show the observations and several selected models with

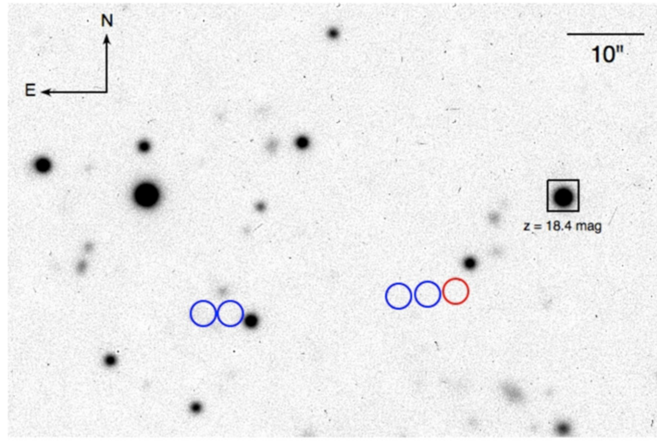

Figure 1. z-band FORS2 observations of the field containing WISE0855-07. Blue circles are *WISE* positions in 2010.34 and 2010.86 (the pair on the left) and *Spitzer* positions 2013.47 and 2014.05 (the pair on the right). The red circle is the expected position of WISE 0855-07 on 2014 May 31. No counterpart to WISE 0855-07 is detected in our z-band FORS2 frames. For reference, the square indicates a source with z(AB) = 18.4 mag.

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

$T_{\rm eff}$ ranging from 200 to 300 K. For each model, we compute the flux expected in the *Spitzer*/IRAC 3.6 μm and 4.5 μm channels and scale the models to the observed *Spitzer* fluxes using the approach described by Rayner et al. (2009). We convert these scale factors to physical radii, which are listed in the figure legend.

None of the models match all the data, but models with $T_{\rm eff} \lesssim 250$ K give the most reasonable agreement. Most notable is that no model faithfully reproduces the observed [3.6]–[4.5] color; models hotter than 300 K begin to match this color, but predict optical/NIR fluxes that would have been easily detected. Moreover, the physical radii of 0.5 and 0.6 $R_{\rm Jup}$ required to fit 300 K Morley et al. and 280 K Burrows et al. models, respectively, are smaller than radii predicted from equations of state of very low-mass objects. A larger coverage fraction of cold clouds for models of $T_{\rm eff}$ = 300 K would give more reasonable radii, but disagrees with the upper limits. The Burrows et al. models show a significant discrepancy with the Morley et al. models at λ < 1.2 μm. The best-fitting Morley et al. 250 K models and cooler, heavily clouded ($h \gtrsim 0.8$ in the nomenclature of Marley et al. 2010 and Morley et al. 2014) models predict z-band fluxes above our detection limit, so our observations nominally exclude these models. Although atmospheric models with $T_{\rm eff}$ = 200 K and a partly cloudy atmosphere (h = 0.5) agree with most published upper limits, they formally disagree with the upper limit of W4 < 9 mag reported by Luhman (2014). Models below ≈200 K have [4.5]–[W4] colors that are excluded by existing data. The coolest models plotted in Figures 2 and 3 predict radii of 1.4 R_{Jup}; this value is larger than predicted by evolutionary models, but would be consistent with an unresolved, near-equal-mass binary. A similar situation holds with the models of Burrows et al. (2003), shown in Figure 3, where the hotter models are too bright in the NIR and the cooler models are too bright at W4. Thus, every model disagrees with the 3.6 μm point and at least one other bandpass. The methane molecular band is the most significant opacity source at 3.6–4.5 μm, therefore the inconsistency between theoretical predictions and observations at this wavelength range might be explained by missing and/or incorrect line opacities. Alternatively, the mismatch between observations and models

[11] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[12] Available through the FORS2 Exposure Time Calculator at http://www.eso.org/observing/etc/.

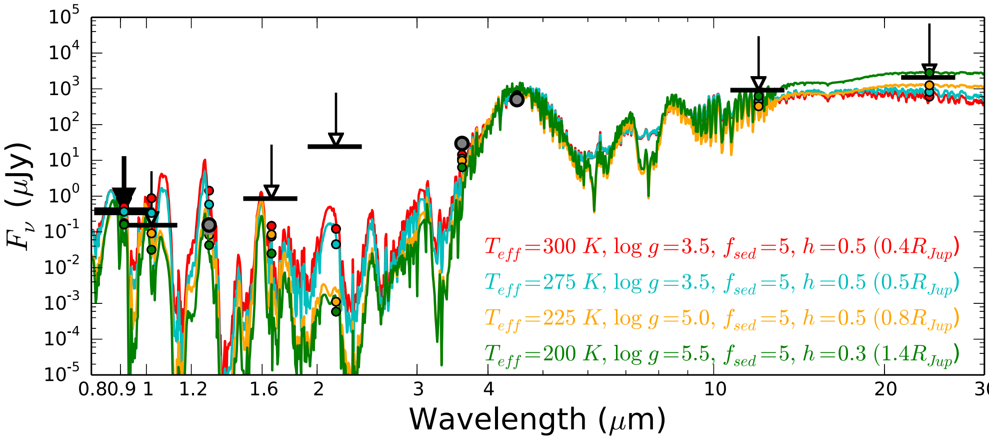

Figure 2. Morley et al. (2014) atmospheric models for various effective temperatures T_{eff}, surface gravities log g, and cloud sedimentation parameters f_{sed}. Large gray filled circles are detections using *WISE* (Wright et al. 2010) and *Spitzer*, and the 2.6σ *J*-band detection by Faherty et al. (2014). Large arrows are upper brightness limits from Luhman (2014), Wright et al. (2014), and Beamín et al. (2014). The small color-coded dots are fluxes in photometric bands predicted by the models. Our upper limit is highlighted at far left. All photometric measurements are on the AB system. The hottest model shown is ruled out both by the upper limits and by the physically implausible radius required to match the detections.

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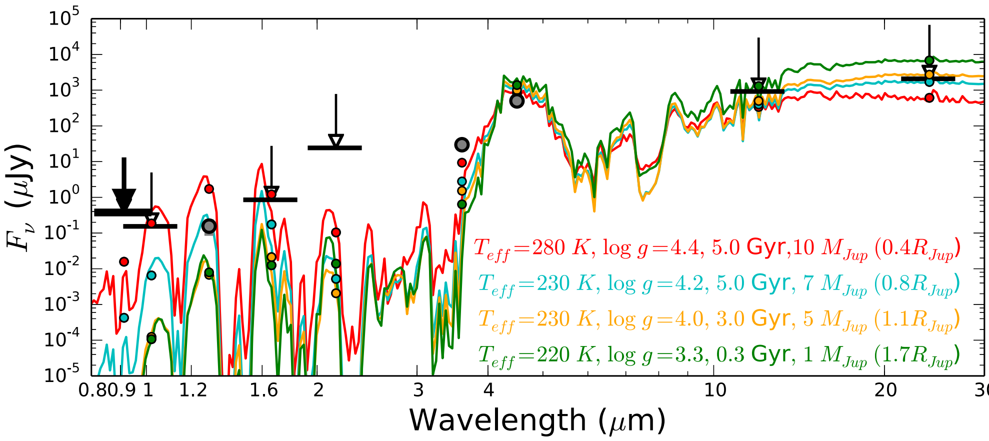

Figure 3. Burrows et al. (2003) atmospheric models for various effective temperatures T_{eff}, surface gravities log g, and ages. Large gray filled circles are detections using *WISE* (Wright et al. 2010) and *Spitzer*, and the 2.6σ *J*-band detection by Faherty et al. (2014). Large arrows are upper brightness limits from Luhman (2014), Wright et al. (2014), and Beamín et al. (2014). The small color-coded dots are fluxes in photometric bands predicted by the models. Our upper limit is highlighted at the far left. All photometric measurements are on the AB system. The hottest model shown is ruled out both by the upper limits and by the physically implausible radius required to match the detections.

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could indicate a more shallow temperature-pressure profile than predicted by current theory or by non-equilibrium chemistry (e.g., vertical mixing) as suggested for some directly imaged giant exoplanets (e.g., Skemer et al. 2014).

Based on the evolutionary models of Saumon & Marley (2008), at an age of 10 Gyr a 200 K object must have a mass $\leqslant 15\ M_{\text{Jup}}$ and radius $\approx 1.0\ R_{\text{Jup}}$. These constraints suggest that WISE 0855-07 should have $\log g \lesssim 4.5$; the plotted model spectrum with the faintest optical/NIR fluxes corresponds to $\log g = 5.0$, which would be formally excluded based on evolutionary considerations. Nonetheless even this model predicts a z-band flux only $\sim 4\times$ fainter than our limit, and the model with 200 K and $\log g = 4$ yields a z-band flux barely fainter than our new constraint; thus, dedicated ground-based observations still have a role to play. Our primary conclusions are therefore that (1) based on the current state-of-the-art models, WISE0855-07 has $T_{\text{eff}} \lesssim 250$ K and (if patchy) $\lesssim$80% of the surface is cloud-covered, and (2) improvements in models of substellar evolution, atmospheres, clouds, and opacities will be necessary to better characterize this object. WISE 0855-07 has the potential to become the first object outside the solar system with detected water clouds in its atmosphere.

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Facilities: VLT:Antu, PS1

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