THE FIRST SPECTRUM OF THE COLDEST BROWN DWARF

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ABSTRACT

The recently discovered brown dwarf WISE 0855 presents the first opportunity to directly study an object outside the solar system that is nearly as cold as our own gas giant planets. However, the traditional methodology for characterizing brown dwarfs—near-infrared spectroscopy—is not currently feasible, as WISE 0855 is too cold and faint. To characterize this frozen extrasolar world we obtained a 4.5–5.2 μm spectrum, the same bandpass long used to study Jupiter’s deep thermal emission. Our spectrum reveals the presence of atmospheric water vapor and clouds, with an absorption profile that is strikingly similar to Jupiter’s. The spectrum quality is high enough to allow for the investigation of dynamical and chemical processes that have long been studied in Jupiter’s atmosphere, but now on an extrasolar world.

Key words: brown dwarfs

1. INTRODUCTION

The coldest characterizable exoplanets are still much hotter than the gas giant planets in our solar system (Kuzuhara et al. 2013; Macintosh et al. 2015). However, with the recent discovery of a ~250 K brown dwarf, WISE J085510.83071442.5 (hereafter WISE 0855), we now have our first opportunity to directly study an object whose physical characteristics are similar to Jupiter (Luhman 2014). WISE 0855 is the nearest known planetary mass object, and the coldest known compact object outside of our solar system (Luhman 2014). Its extremely low temperature makes it the first object after Earth, Mars, Jupiter, and Saturn that is likely to host water clouds in its visible atmosphere (Marley et al. 1999; Sudarsky et al. 2000; Faherty et al. 2014).

A handful of photometric detections and non-detections confirm that W0855 is cold, but they only allow us to speculate on its atmospheric composition (Beamín et al. 2014; Faherty et al. 2014; Kopytova et al. 2014; Wright et al. 2014). WISE 0855 is too faint to characterize with conventional spectroscopy in the optical or near-infrared (<2.5 μm). Like Jupiter, a minimum in CH4 and H2 gas opacity allows thermal emission from the deep atmosphere to escape through a 5 μm atmospheric window (Low & Davidson 1969; Bjoraker et al. 1986a, 1986b). Spectroscopy at these wavelengths is challenging but not impossible. While there are currently no space-based facilities capable of 5 μm spectroscopy, ground-based telescopes can observe through the Earth’s 4.5–5.2 μm atmospheric window, although sensitivity is limited by the brightness of the Earth’s sky. With careful calibration, we were able to obtain a spectrum of WISE 0855, an object that is five times fainter than the faintest object previously detected with ground-based 5 μm spectroscopy (Geballe et al. 2009; Wright et al. 2014).

2. OBSERVATIONS

We observed WISE 0855 with the Gemini-North telescope and the Gemini Near Infrared Spectrograph (GNIRS; Elias et al. 2006). Gemini-North is located near the summit of Mauna Kea, a cold location that also provides some of the driest conditions of any astronomical site in the world. Because of those attributes, as well as the telescope’s low emissivity, the infrared background incident on Gemini’s instruments is the lowest of any 8–10 m class telescope. Additionally, Gemini-North is operated in queue-mode, allowing us to observe WISE 0855 over many nights in clear, dry and calm conditions. In total, we observed WISE 0855 for 14.4 hr over 13 nights. We calibrated the transmission of the Earth’s atmosphere by observing standard stars before and after every observation of WISE 0855.

GNIRS was configured with its long-wavelength camera, 31.7 line mm−1 grating and 0″675 slit, which provides a single order spectrum covering the M-band (4.5–5.2 μm) at a spectral resolution of R ~ 800. Although GNIRS is typically used with its fastest readout mode for broad M-band spectroscopy, we found that there was still appreciable read-noise at some wavelengths, and decided to operate in its second fastest mode, which uses 16 digital averages and has an overhead of 0.6 s per frame. In order to keep our observations of WISE 0855 efficient, we integrated for 2.5 s, which is enough to saturate the brightest M-band skylines. These wavelengths were then masked in our later analysis.

Observing conditions in the Gemini queue were limited to photometric conditions, <0.8 seeing at the V-band, <3 mm precipitable water vapor, and <1.5 airmass. Telluric calibrators (HIP 39898 and HIP 49900) were obtained at similar airmasses before and after each observation, with a maximum separation of 2 hr.

Because WISE 0855 is essentially invisible in the near-infrared (Beamín et al. 2014; Faherty et al. 2014; Kopytova et al. 2014), acquisitions were done using a blind offset from a
3. REDUCTIONS

We reduced the data using a modified version of the REDSPEC package\(^9\) to spatially and spectrally rectify each exposure with the dispersion direction as “rows” and the spatial direction as “columns.”

For each data set, we first create a nonlinearity flag image by marking pixels with values greater than 10,000 counts per coadd. We then median-scale the images and create nod-subtracted A–B pairs.

Observations of the telluric standards are used to create the spatial and spectral maps, which are then used to rectify the WISE 0855 data. The spatial rectification process uses a subtracted A–B pair of telluric star exposures, fits Gaussians to find the center of each star as a function of wavelength, and then fits a second order polynomial to define a trace. These traces are then used to remap each exposure so that the dispersion direction lies along detector rows. To wavelength calibrate and spectrally rectify our exposures, we use sky emission lines in our telluric standard spectra. We determined the wavelengths of 11 skylines by smoothing a model of the sky background for Mauna Kea\(^10\) to match the R ∼ 800 resolution of our GNIRS spectra. We use a second order polynomial to fit a dispersion solution to each spectral trace, which is then used to remap each exposure so that each column corresponds to a single wavelength. The residuals for our dispersion fits are <2 pixels, or 0.0013 μm.

For each rectified A–B pair image, we remove residual skylines from each column by subtracting that column’s median value. We combine the rectified, background-subtracted A–B pairs with a 3-σ clipped mean at each pixel. The uncertainty of each pixel in the stacked image is the standard deviation of the mean.

To extract the spectrum, we create a wavelength-collapsed spatial cut by taking the median of each row in the stacked A–B image, and boxcar-smoothing the profile by 5 pixels (0′′.25). We identify the location of the A and B spectra by fitting two Gaussians to the spatial cut. We then extract each spectrum using an aperture radius of ∼1.6σ (where σ is the width of the Gaussian fit to the spatial cut), and subtract any residual sky background by fitting a line to the background regions. If a pixel that was flagged as nonlinear falls in the aperture, the spectrum at that wavelength is also flagged. For each data set, our reduction results in an A and a B spectrum. We extract the spectra of our telluric standard stars using a similar process.

We divide each extracted spectrum of WISE 0855 by the spectrum of an adjacent telluric standard, and multiply by an appropriate blackbody. When using the calibrator HIP 39898, there is an additional step to remove its Pfund β emission by fitting and subtracting a Gaussian. In most cases, the airmass of our WISE 0855 observation matched the airmass of the telluric observation to within 0.1. In total, we have 48 telluric calibrated spectra of WISE 0855, which we combine using a robust weighted mean (Cushing et al. 2004).

We binned the data in 20 pixel increments for presentation in this paper (spectral resolution of ∼300 per point, or ∼150 for Nyquist sampling). Within each bin, we calculated the weighted average and weighted error, which has the effect of suppressing wavelengths with large telluric emission (and low transmission) features. Our calibrated spectrum of WISE 0855 is presented in Figure 1. For subsequent spectrum plots in this paper, identical weights are applied to comparison spectra, and are used to calculate each bin’s effective wavelength.

In addition to making the spectrum intelligible, binning the data smooths wavelength mismatch errors between WISE 0855 and the telluric calibrators, which would result from WISE 0855 being slightly misaligned in the oversized slit. To confirm that the wavelength mismatch errors did not affect our final spectrum, we re-reduced the data assuming a 0′′.2 slit misalignment for WISE 0855 and found negligible differences.

The overall quality of our data reduction process and telluric correction is validated by dividing the spectra of our pre- and post-observation telluric calibrators, averaged over the 13

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\(^9\) \url{http://www2.keck.hawaii.edu/inst/nirspec/redspec}

\(^10\) \url{http://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/ir-background-spectra}
We vary the cloud-O$_2$H$_2$O$_2$ age relatively insensitive to unknown parameters, such as WISE 0855’s measured luminosity and a radius estimate that is effective temperature of 250 K, which is well-constrained from custom atmospheric models. All of our models have an thermal radiative transfer is determined using the "source function technique" presented in Toon et al. (1989). The gas opacity is calculated using correlated-k coefficients; our opacity database is described extensively in Freedman et al. (2008) and Freedman et al. (2014). The atmosphere models are more extensively described in McKay et al. (1989), Marley et al. (1996), Marley et al. (1999), Marley et al. (2002), Fortney et al. (2008), and Saumon & Marley (2008).

Exoplanets and brown dwarfs that are cooler than $\sim$350 K are expected to form water ice clouds in their upper atmospheres, which are optically thick enough to alter the emergent spectrum (Marley et al. 1999; Sudarsky et al. 2000; Burrows et al. 2003; Morley et al. 2014). We find that partly cloudy models (Morley et al. 2014) are indistinguishable from cloud-free models after normalizing and binning over the wavelength range of our WISE 0855 spectrum. Radiative-convective equilibrium models with full water cloud coverage do not converge well between $T_{\text{eff}} \sim$ 200 and 450 K (Morley et al. 2014).

For this reason, we use a simplified approach to consider the effect of clouds at different layers, following studies of Jupiter’s mid-infrared spectral features (Bjoraker et al. 2015). We calculate the pressure–temperature profile of a cloud-free atmosphere in radiative-convective equilibrium. We then use that profile and calculate the thermal emission using an adapted version of DISORT (Morley et al. 2015) including a gray, fully absorbing cloud with optical depth $\tau = 1$. We vary the cloud-top pressure of this gray cloud to best match the observed spectrum of WISE 0855.

We also use the DISORT radiative transfer scheme to model the effect of non-equilibrium abundances of trace gases such as PH$_3$ and CH$_3$D. We first calculate a cloud-free profile in chemical equilibrium, and then calculate spectra in which we change the abundance of each gas separately, changing the mixing ratio of that gas to be uniform at that value throughout the atmosphere.
Our model temperature–pressure profile for \textit{WISE} 0855 and the next coldest brown dwarf with a 5 \(\mu\)m spectrum (Gl 570D; 700 K Sorahana & Yamamura 2012) are shown in Figure 3, along with a measured profile for Jupiter (Seiff et al. 1998) extrapolated along an adiabat to lower depths. Jupiter and \textit{WISE} 0855 have relatively similar temperature–pressure profiles, thus their photospheres should display similar features. Both photospheres are near the condensation temperatures for \(H_2O\) and \(NH_3\) clouds. Under equilibrium chemistry assumptions, neither photosphere should have detectable amounts of \(PH_3\).

5. DISCUSSION

5.1. Composition and Clouds

Our equilibrium chemistry models from Section 4 predict that for a 250 K object, all of the major absorption features from 4.5 to 5.2 \(\mu\)m are the result of water vapor. Figure 4(a) shows cloudy and cloud-free models compared to the \textit{WISE} 0855 spectrum. The wavelengths of the model features match the wavelengths of the spectrum features, which suggests that our \textit{WISE} 0855 spectrum is dominated by water vapor.

The cloudy model is a better fit to the depths of \textit{WISE} 0855’s absorption features, as well as its overall slope. While our model does not specify a particular cloud composition, \textit{WISE} 0855 is at a temperature where the clouds are likely to be composed of water or water ice (Burrows et al. 2003; Morley et al. 2012). The cloudy model’s fit to \textit{WISE} 0855 is imperfect, which suggests that there is additional complexity that is beyond the scope of our current models. For example, the particular vertical and horizontal structure of the clouds is likely to impact \textit{WISE} 0855’s appearance.

5.2. Comparison with Jupiter

We compare our spectrum of \textit{WISE} 0855 to a full-disk spectrum of Jupiter in Figure 4(b). From 4.8 to 5.2 \(\mu\)m, \textit{WISE} 0855 and Jupiter are strikingly similar, as Jupiter’s atmosphere is also dominated by \(H_2O\) absorption at these wavelengths (Kunde et al. 1982). From 4.5 to 4.8 \(\mu\)m, Jupiter’s...
spectrum is dominated by PH$_3$ (phosphine) absorption (Kunde et al. 1982). If Jupiter were in chemical equilibrium, phosphorous would exist in the form of P$_2$O$_5$ in its photosphere and PH$_3$ in its hotter interior (Prinn & Lewis 1975; Visscher et al. 2006). The existence of PH$_3$ in Jupiter’s spectrum is evidence that Jupiter’s atmosphere turbulently mixes gases from its hot interior into its cooler photosphere on a faster timescale than the PH$_3$ → P$_2$O$_5$ reaction sequence can reach equilibrium (Prinn & Lewis 1975; Visscher et al. 2006).

### 5.3. PH$_3$ Chemistry and Mixing

WISE 0855s spectrum does not show the strong PH$_3$ absorption seen in Jupiter’s spectrum. In Figure 4(c), we show our equilibrium chemistry model for WISE 0855, along with a model that has PH$_3$ enhanced to the abundance measured in Jupiter (Lodders 2010). If WISE 0855 had Jupiter’s abundance of PH$_3$, it would easily be visible in our spectrum. The fact that WISE 0855 has less PH$_3$ than Jupiter most likely implies that WISE 0855 has less turbulent mixing than Jupiter, although atmospheric metallicity and gravity may also play a role.

### 5.4. Deuterium

Figure 4(d) shows a comparison of WISE 0855 with models that vary CH$_3$D (deuterated methane). Deuterium is expected to be quickly depleted by fusion in objects more massive than ~13 M$_{\text{Jup}}$, a boundary commonly used to separate planets from brown dwarfs (Burrows et al. 1997; Spiegel et al. 2011). Thus, CH$_3$D measurements can be used to glean information about the masses of exoplanets and free-floating planets/brown dwarfs. In our solar system, deuterium becomes chemically concentrated in certain environments, and has been used to study the formation of the giant planets, and the delivery of water to Earth (Owen et al. 1986; Altwegg et al. 2015). In multi-planet extrasolar systems, CH$_3$D measurements could similarly be used to study the composition of the planets’ nascent materials.

Our spectrum has the sensitivity to distinguish between models with Jupiter’s approximately primordial deuterium abundance (Owen et al. 1986; Lodders 2010), and models with no deuterium. However, the CH$_3$D absorption feature is blended with water absorption features, which need to be better understood before we can really measure CH$_3$D.

### 6. FUTURE PROSPECTS

To understand the nature of clouds and vertical mixing in cold gas giants, we need 5 μm spectra of objects across a continuum of temperatures. After Jupiter (130 K) and WISE 0855 (250 K), the next coldest object with a 5 μm spectrum is Gl 570D (700 K) (Sorahana & Yamamura 2012). In the near term, ground-based telescopes have the sensitivity to obtain spectra of a handful of objects in this temperature range. Future facilities, like the James Webb Space Telescope, will have the sensitivity to characterize cold gas giants with higher precision, and at wavelengths not possible from Earth (Morley et al. 2014). The next generation of ground-based telescopes (Extremely Large Telescopes) will have the angular resolution and sensitivity to study systems with multiple exoplanets that look like WISE 0855. With spectrographs operating in the 5 μm atmospheric window (Skemer et al. 2015), it will be possible to compare large samples of exoplanets at wavelengths that have revealed much of what we know about gas giants in our own solar system.

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