Title: Characterizing a Frozen Extrasolar World

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Abstract: The recently discovered brown dwarf WISE 0855 presents our first opportunity to 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. The spectrum is high enough quality to allow the investigation of dynamical and chemical processes that have long been studied in Jupiter's atmosphere, but this time on an extrasolar world.

One Sentence Summary: The first spectrum of the coldest brown dwarf is dominated by water vapor and clouds, with an appearance that is strikingly similar to Jupiter.

Main Text: The coldest known exoplanets are still much hotter than the gas giant planets in our Solar System *(1,2)*. However, with the recent discovery of a ~250 K brown dwarf, WISE 0855, we now have our first opportunity to study an object whose physical characteristics are similar to Jupiter *(3)*. WISE 0855 is the nearest known planetary mass object, and the coldest known compact object outside of our Solar System *(3)*. Its extremely low temperature makes it the first object after Earth, Mars and Jupiter likely to host water clouds in its visible atmosphere *(4)*.

A handful of photometric detections and non-detections are enough to tell us that WISE 0855 is cold, but not much else *(3-7)*. WISE 0855 is too faint to characterize with conventional spectroscopy in the optical or near infrared (<2.5 μm). Its peak emission, like Jupiter, is through a 5 μm atmospheric window *(8)*. 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 5 times fainter than the faintest object previously detected with ground-based 5 μm spectroscopy *(5,9)*.

We observed WISE 0855 with the Gemini-North telescope and the Gemini Near Infrared Spectrograph (GNIRS) *(10)*. 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 meter 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 hours over 13 nights. We calibrated the transmission of the Earth's atmosphere by observing standard stars before and after every observation of WISE 0855.

Our calibrated spectrum of WISE 0855 is presented in Fig. 1. Also displayed is a model of a 250 K atmosphere with clouds inserted at a depth that best matches the shape of the WISE 0855 spectrum *(11,12)*. All of the major absorption features in the model are due to water vapor. The wavelengths of these features match the wavelengths of features in the WISE 0855 spectrum, which suggests that WISE 0855's spectrum is dominated by water vapor.

Clouds are an important characteristic in the appearance of planets and brown dwarfs *(13-18)*. Fig. 2a shows the WISE 0855 spectrum compared to a cloudy model and a cloud-free model. The cloudy model is a better fit to the depths of WISE 0855's absorption features, as well as its overall slope. While our model does not specify a particular cloud composition, WISE 0855 is at a temperature where the clouds are likely to be composed of water or water ice *(15,16)*. The cloudy model's fit to 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 WISE 0855's appearance.

We compare our spectrum of WISE 0855 to a full-disk spectrum of Jupiter in Fig. 2b. From 4.8-5.2 µm, WISE 0855 and Jupiter are strikingly similar, as Jupiter's atmosphere is also dominated by H_2O absorption at these wavelengths *(20)*. From 4.5-4.8 µm, Jupiter's spectrum is dominated by PH_3 (phosphine) absorption *(20)*. If Jupiter were in chemical equilibrium, phosphorus would exist in the form of P_4O_6 in its photosphere, and PH_3 in its hotter interior *(21,22)*. The existence of PH_3 in Jupiter's spectrum is evidence that Jupiter's atmosphere turbulently mixes gasses from its hot interior into its cooler photosphere on a faster timescale than the PH_3->P_4O_6 reaction sequence can go to equilibrium *(21,22)*.

WISE 0855's spectrum does not show the strong PH_3 absorption seen in Jupiter's spectrum. In Fig. 2c, we show our equilibrium chemistry model for WISE 0855, along with a model that has PH_3 enhanced to the abundance measured in Jupiter. 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.

Fig. 2d shows a comparison of WISE 0855 with models that vary CH_3D (deuterated methane). Our spectrum has the sensitivity to distinguish between models with Jupiter's approximately primordial deuterium abundance *(23)*, and models with no deuterium. However, the CH_3D absorption feature is blended with water absorption features, which need to be better understood before we can really measure CH_3D.

Deuterium is expected to be quickly destroyed in brown dwarfs with masses greater than ~13 M_{jup}, a boundary commonly used to divide planets from brown dwarfs *(13,24)*. Thus, CH_3D 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 *(23,25)*. In multi-planet extrasolar systems, CH_3D measurements could similarly be used to study the composition of the planets' nascent materials.

Jupiter and WISE 0855's overall similarities are summarized in Fig. 3. The objects have relatively similar temperature-pressure profiles, thus their photospheres should display similar features. Both photospheres are near the condensation points for H_2O and NH_3 clouds, and indeed, WISE 0855's spectrum suggests that it has clouds, as does Jupiter. Under equilibrium chemistry assumptions, neither photosphere should have detectable amounts of PH_3, but Jupiter does and WISE 0855 does not, a discrepancy that requires further modeling.

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) *(26)*. 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* (JWST), will have the sensitivity to characterize cold gas giants with higher precision, and at wavelengths not possible from Earth *(11)*. The next generation of ground-based telescopes (Extremely Large Telescopes, or ELTs) 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 *(27)*, it will 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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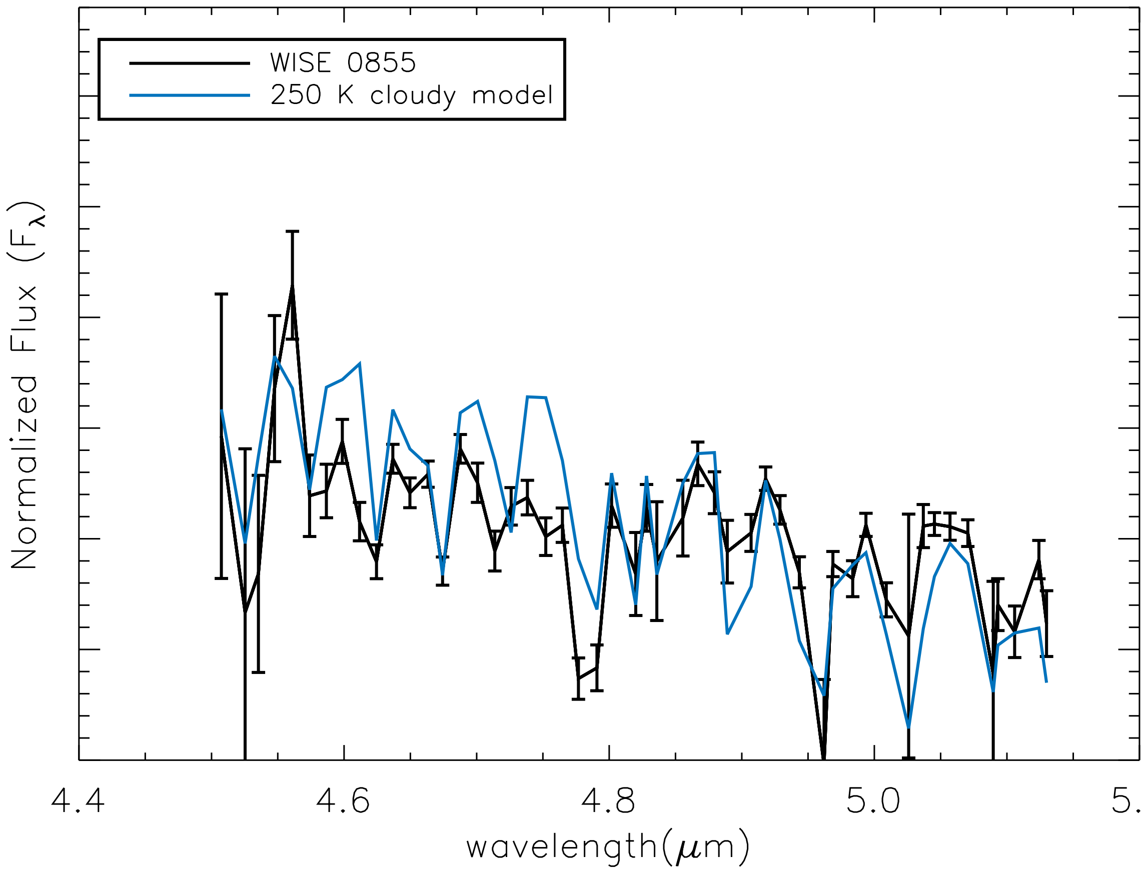

Fig. 1. Gemini/GNIRS spectrum of WISE 0855 compared to a model of a 250 K brown dwarf *(11,12)*. The model and data are both dominated by water vapor absorption. The spectra are normalized because the Gemini/GNIRS data are insensitive to overall flux. The choice of a 250 K model is set by the object's luminosity and a radius estimate that is relatively insensitive to unknown parameters, such as WISE 0855's age *(3)*.

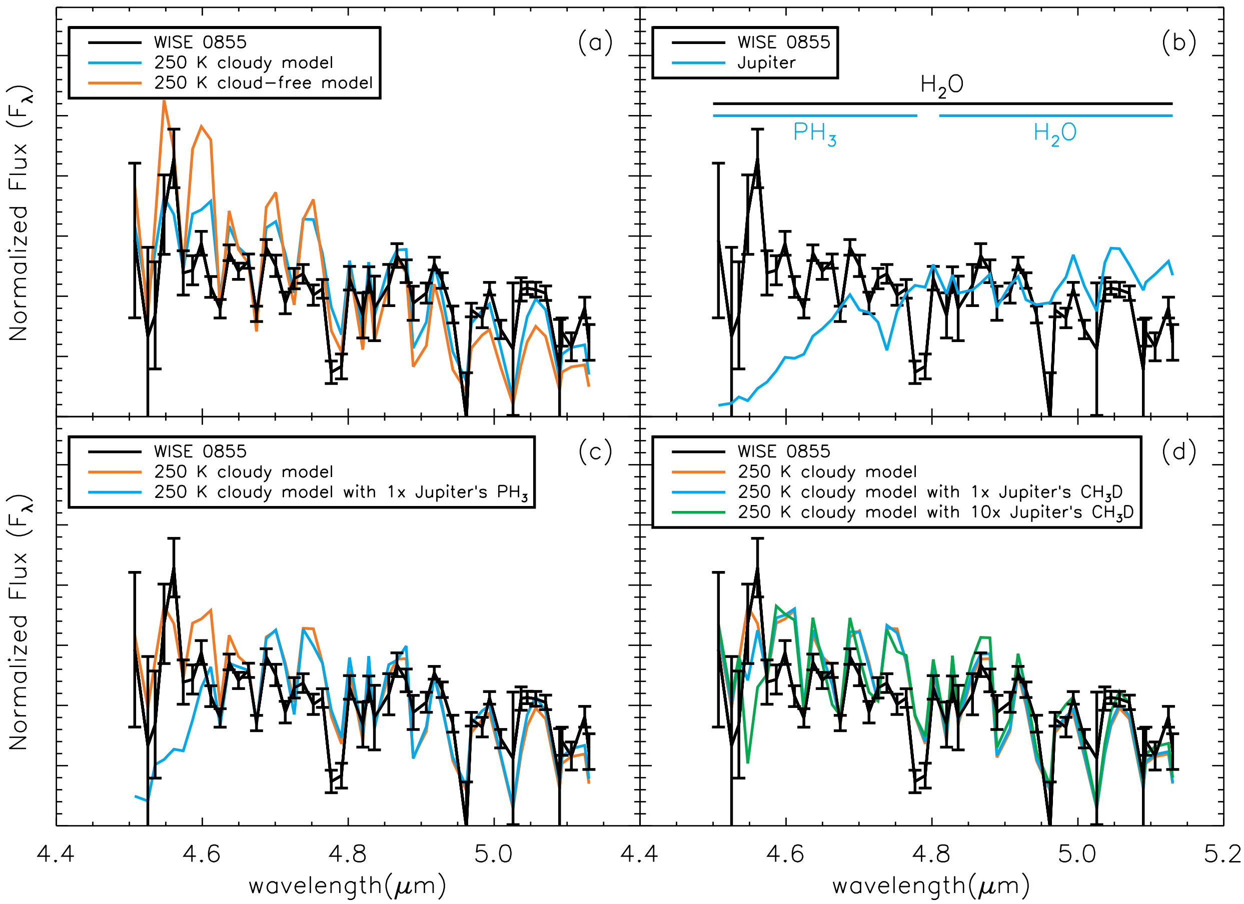

Fig. 2. (a) Gemini/GNIRS spectrum of WISE 0855 compared to cloudy and cloud-free brown dwarf models. A partially opaque cloud layer in the photosphere (2.5 bars) mutes the absorption features providing a better fit between the model and the data. Similar methods are used to infer the presence of clouds deep in Jupiter's hot spots *(12)*. Clouds at 2.5 bars in WISE 0855 are likely to be composed of water or water ice *(15,16, Fig.3)*. The remaining discrepancies between the cloudy model and the data are likely due, in part, to additional complexities (such as 3-dimensional structures) of the clouds. (**b**) Gemini/GNIRS spectrum of WISE 0855 compared to a full-disk spectrum of Jupiter from the Infrared Space Observatory (ISO) (*19)*, binned to WISE 0855's resolution. The spectra show striking similarities from 4.8-5.2 µm, as both objects are dominated by H_2O *(20)*. From 4.5-4.8 µm, Jupiter's spectrum is dominated by PH_3, which has

been used to infer turbulent diffusion of hot material from deep in Jupiter's atmosphere *(20-22)*. The WISE 0855 spectrum does not show a similar PH_3 feature. **(c)** Gemini/GNIRS spectrum of WISE 0855 compared to models with equilibrium chemistry PH_3, and enhanced PH_3 to match the abundance measured in Jupiter. The WISE 0855 spectrum is strongly inconsistent with the enhanced PH_3 model, suggesting that WISE 0855 does not have the same turbulent mixing seen on Jupiter. **(d)** Gemini/GNIRS spectrum of WISE 0855 compared to models that vary CH_3D abundance. The WISE 0855 spectrum has the raw sensitivity to measure CH_3D at 4.55 μm, but the imperfect match between the rest of the spectrum and our current model would hamper an analysis. Because deuterium is expected to burn in objects more massive than ~13 M_{jup}, CH_3D can be used to crudely measure exoplanet masses.

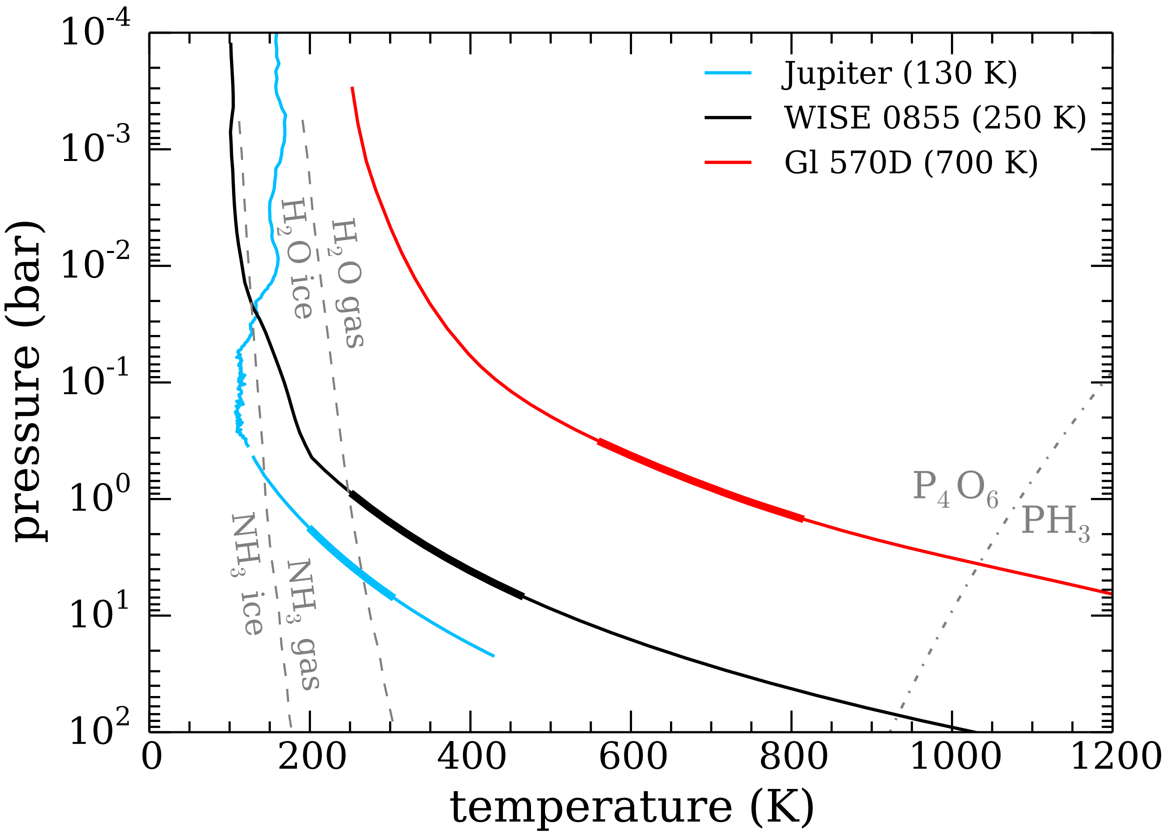

Fig. 3. Temperature-pressure profiles of Jupiter, WISE 0855, and what was previously the coldest extrasolar object with a 5 µm spectrum, Gl 570D *(26)*. The approximate locations of each object's 5 µm photosphere are denoted with thicker lines (for Jupiter, the photosphere is as seen through cloud-free hot-spots). Two dashed lines show the boundaries where H_2O gas and NH_3 gas begin to condense into clouds composed of H_2O ice and NH_3 ice. A dot-dash line divides the regions where phosphorus is primarily in P_4O_6 versus PH_3 under equilibrium chemistry assumptions. WISE 0855 and Jupiter have relatively similar temperature-pressure profiles, with photospheres that are in the vicinity of the condensation points for NH_3 and H_2O. However, PH_3 is mixed high up into the photosphere of Jupiter, while it is not seen in WISE 0855's spectrum.