Towards Robust Atmospheric Retrievals for Cloudy L Dwarfs: Tests on T Dwarf Spectra

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Abstract

Retrieving atmospheric properties from spectra is the only method through which properties of brown dwarf atmospheres can be determined since in situ measurements are impossible at astronomical distances. But to date, retrieval frameworks with clouds have not been robustly verified for accuracy despite the fact that clouds are abundant in cooling brown dwarfs. The overarching goal of my thesis work is to incorporate the more complex physics governing cloud formation into retrieval frameworks for cloudy L dwarf atmospheres and later for cloudy planetary atmospheres. Before this goal can be accomplished, we must first test a number of assumptions regarding thermal structure, chemical equilibrium, and uniform chemical abundances on the more straightforward and relatively cloud-free T dwarf emission spectra. Preliminary results for the benchmark T dwarf Gl 570D are presented.

Introduction

Retrieving atmospheric properties from spectra is the only method through which properties of brown dwarf and exoplanet atmospheres can be determined since in situ measurements are impossible. In order to successfully model the complex atmospheres of cloudy substellar objects, various assumptions that are inherent in retrieval frameworks first need to be better understood. These assumptions include chemical equilibrium, thermal structure, and uniform chemical abundances.

While some recent retrieval frameworks have started to depart from these assumptions, a systematic examination of the effect of each of these assumptions on retrieved emission spectra has not been undertaken. Therefore, our goal is to systematically examine the effect of these assumptions on more simple, relatively cloud-free T dwarf emission spectra. In service of this goal, the CHIMERA retrieval framework needs to be modified for use on GPU-enabled supercomputers like Frontera and Maverick2 at the Texas Advanced Computing Center (TACC).

Models

We used the GPU-enabled CHIMERA retrieval framework developed by Line et al. (2015)[1] on the benchmark T dwarf Gl 570D. We modified CHIMERA for use on Frontera and Maverick2, two GPU-enabled supercomputers at TACC. This retrieval framework uses emcee[2] as the statistical retrieval framework. The forward model incorporates the effects of multiple scattering. It uses a free temperature-pressure (TP) profile parameterization with temperatures retrieved at 15 pressure levels, which are then interpolated to a finer pressure grid. Uniform volume mixing ratios for H_2O, CH_4, CO, CO_2, NH_3, K, and Na are retrieved. Surface gravity and a scale factor that places a constraint on object radius are also retrieved.

The effect of assumptions regarding the temperature profile, chemical equilibrium, and uniform chemical abundances will be tested through modification of the forward model. A retrieval on low resolution SpeX data from the Brown Dwarf Spectra Library[3] of the benchmark T dwarf Gl 570D serves as a preliminary test of some of these assumptions in the brown dwarf regime.

To investigate the efficacy of using uniform-with-pressure chemical abundances in brown dwarf retrievals, we used the Sonora self-consistent cloud-free models[4] calculated for a log(g) of 5 over a range of temperatures relevant for brown dwarfs. The volume mixing ratios for many gas species are calculated at each pressure level. These self-consistent models are too computationally expensive to be used in retrievals, but the more complex treatment of relevant physics provide insight for where uniform abundances are no longer a valid assumption.

References

[1]Line, M. et al., ApJ, 807, 183 (2015)
[2]Foreman-Mackey, D. et al., PASP, 125, 925 (2013)
[3]Burgasser, A. J., & Splat Development Team, ASICS, 14, 7 (2017)
[4]Marley, M. et al, in prep
[5]Ackerman, A. S. & Marley, M. S., ApJ, 556, 872 (2001)

Results

We retrieved H-band calibrated SpeX spectral data for the benchmark T dwarf Gl 570D using emcee and a forward model that incorporates multiple scattering while utilizing a free TP profile parameterization and uniform-with-pressure chemical abundances. The data and the retrieved spectrum are shown in Figure 1. We retrieve a log(g) of 5.04 ± 0.34 (cgs) and abundances as follows: H_2O: -3.05 ± 0.12, CH_4: -2.96 ± 0.16, CO: -8.4 ± 2.5, CO_2: -8.1 ± 2.5, NH_3: -4.41 ± 0.17, K: -7.32 ± 0.18, and Na: -9.4 ± 1.7.

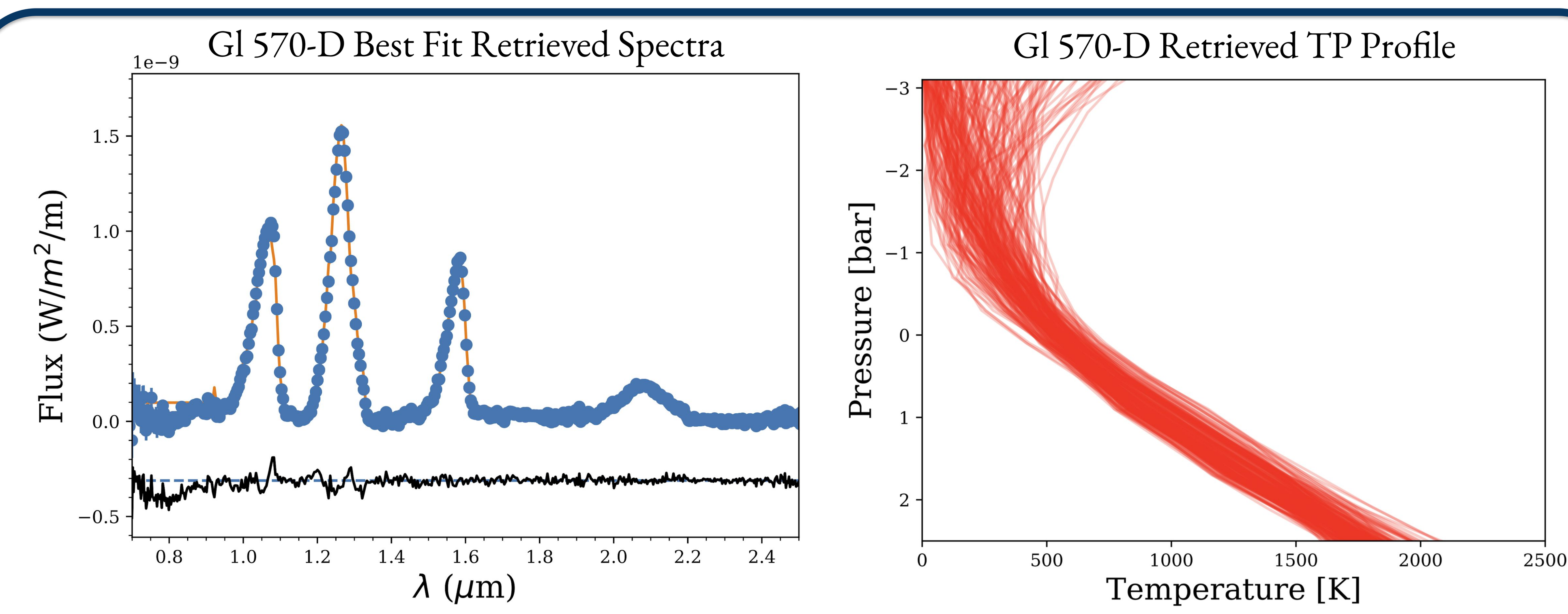

Figure 1. *Retrieval results of benchmark T dwarf Gl 570-D. [L] Best fit retrieved model spectra (orange) of SpeX data (blue). [R] Retrieved temperature pressure profile.*

We compared the uniform-with-pressure chemical abundances with chemical abundances from the Sonora self-consistent cloud-free models for a log(g) of 5. We show a variety of temperatures relevant for L dwarf spectra. These models indicate that while a uniform abundance parameterization may be sufficient for the hottest L dwarfs, it is not sufficient for most gases at cooler temperatures. Volume mixing ratios of H_2O, Fe, CO, CH_4, Na, and K are shown in Figure 2.

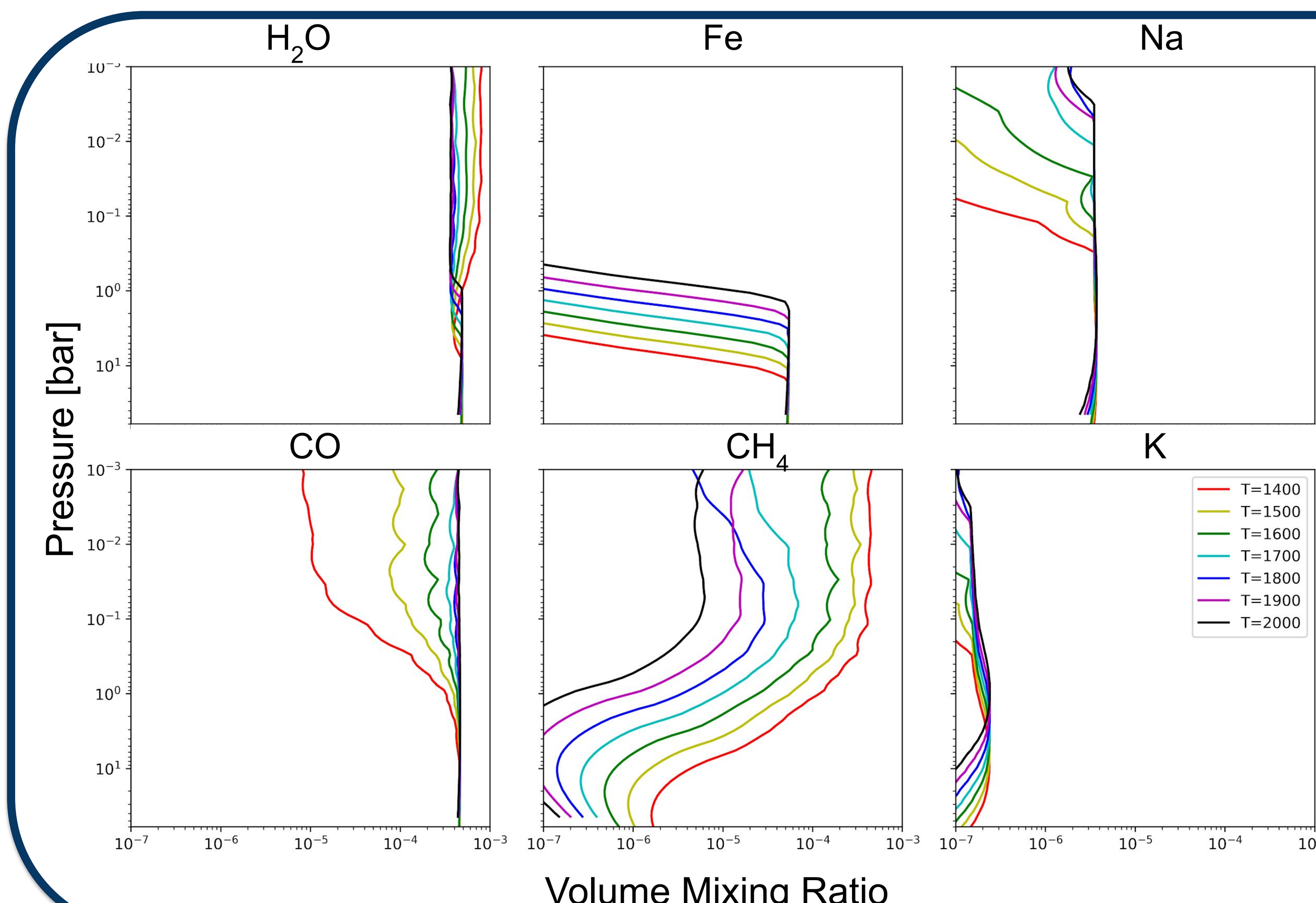

Figure 2. *Shows the chemical abundances of 6 species from self-consistent, cloud-free models calculated for a log(g) of 5. Colors indicate the temperature of models spanning the L dwarf temperature regime. The models indicate that an assumption of uniform abundances is not sufficient for cooler L dwarfs.*

Conclusions and Next Steps

The retrieval Gl570D demonstrates the viability of using the GPU-enabled CHIMERA on TACC. The forward model currently utilizes a "free" temperature profile and retrieves 15 temperatures, uniform-with-pressure chemical abundances, surface gravity, and a scale factor related to radius on T dwarf SpeX data. Preliminary results of Gl 570D show surface gravity and abundances of CO, CO_2, and NH_3 that agree with results from Line et al. 2015 with slightly higher abundances of H_2O and CH_4.

Self-consistent models indicate that uniform abundance parameterizations are insufficient for late L dwarfs. Further, uniform abundances fail to account for disequilibrium chemistry that may be present in cloudy objects. This highlights the need to test non-uniform chemical abundance parameterizations that incorporate disequilibrium chemistry in retrieval frameworks. We will test these changes on cloud-free T dwarfs retrievals before applying them to cloudy L dwarfs.

Implementation of a more structured TP profile will also be tested to break the degeneracy between clouds and isothermal TP profiles. After exploring the impact of these assumptions, we will adapt this framework for use with the Ackerman & Marley cloud model[5] to retrieve atmospheric properties of cloudy L dwarfs. We have been awarded the 2020 FINESST grant to continue this research, which is necessary for future exoplanet science conducted with JWST and direct imaging facilities.