Bayesian Spectroscopic Characterization of Brown Dwarfs and Implications for Model Atmospheres

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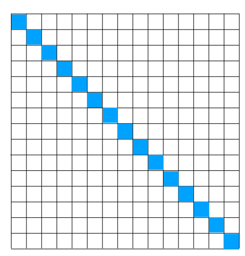
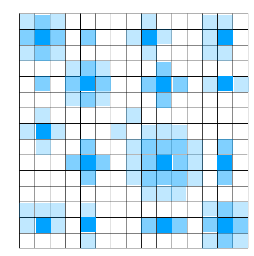
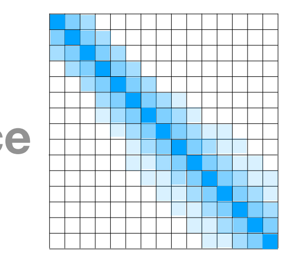
Context

Spectroscopic characterization of brown dwarfs is essential for understanding their atmospheres, formation, and evolution, but such work is challenged by the unavoidably simplified model atmospheres needed to interpret spectra. While most previous work has focused on single or at most a few objects, comparing a large collection of spectra to models can uncover trends in data-model inconsistencies needed to improve models of ultracool atmospheres, thereby leading to robust properties from cool star spectra. Therefore, we are conducting a systematic analysis of a valuable but underutilized resource: **the numerous high-quality spectra of (free-floating or companion) brown dwarfs already accumulated by the community**.

Our Forward-Modeling Framework

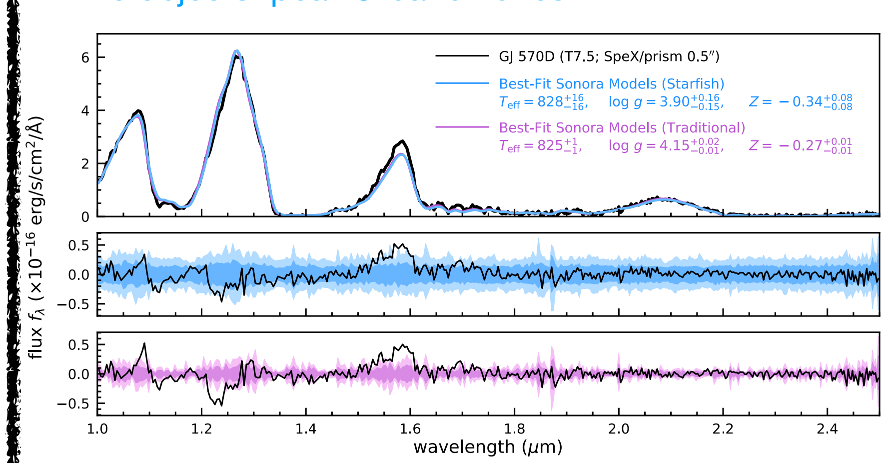
- We use the Cloudless Sonora Model Atmospheres (Marley et al. 2017) and the Bayesian inference tool Starfish (Czekala et al. 2015)
- We infer effective temperature ($T_{\rm eff}$), surface gravity (log g), metallicity (Z), radii (R), and mass (M) for near-infrared (1.0-2.5μm) low-resolution (R~50-250) spectra.
- We account for uncertainties from model interpolation and correlated residuals due to instrumental effects and model systematics.
- We validate our framework by fitting the original model spectra using Starfish and finding negligible offsets between derived and input parameters.

Final Covariance Matrix = Traditional Covariance Matrix  + Emulator Covariance Matrix  + Global Covariance Matrix 

Forward-Modeling Analysis of Late-T Brown Dwarfs

★ The Largest Spectroscopic Analysis of Brown Dwarfs

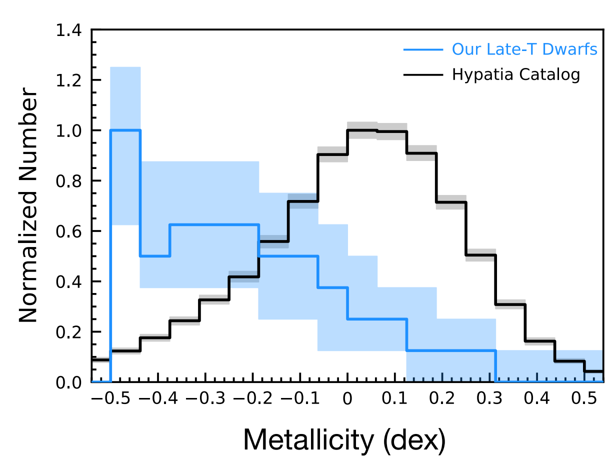
- We study 55 T7—T9 brown dwarfs with IRTF/SpeX spectra and parallaxes.
- We find inferred {$T_{\rm eff}$, log g, Z} errors are ~1/3–1/2 of model grid spacing.
- We quantify the log g-Z degeneracy, as $\Delta\log g \sim 3.4 \times \Delta Z$.
- We assess the systematics of the cloudless Sonora models are ~2%—4% of the objects' peak J-band fluxes.

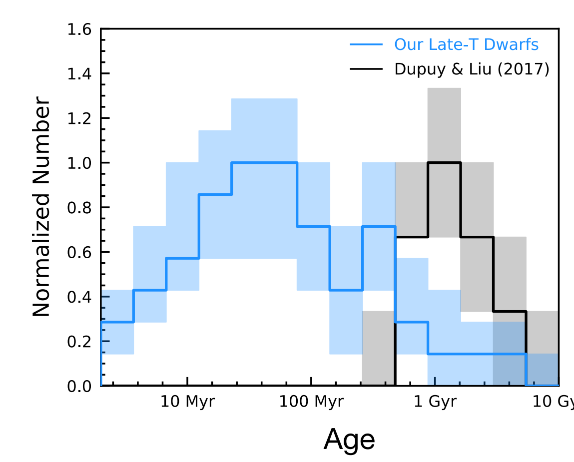


Our framework derives robust parameters and more realistic errors than the traditional spectral-fitting approach.

★ Metallicity & Age Distributions

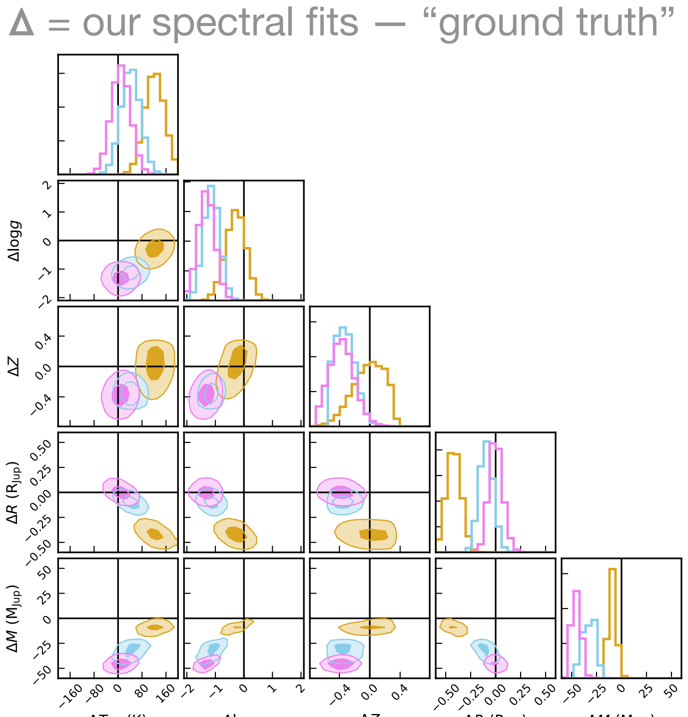
- Our work is the largest homogeneous study of brown dwarf metallicities.
- Our spectroscopically inferred Z are 0.3–0.4 dex lower than nearby FGKM stars from the Hypatia catalog (Hinkel et al. 2014, 2016, 2017).
- Our spectroscopically inferred age are implausibly younger than the robust age based on the M8—T5 dynamical-mass sample (Dupuy & Liu 2017).





★ Benchmarking against Wide-orbit Companions

Δ = our spectral fits — "ground truth"



HD 3651B **GJ 570D**

Our spectral fits infer:
- accurate $T_{\rm eff}$ and R
- underestimated log g (~1.2 dex)
- underestimated Z (~0.35 dex)

likely due to the model systematics from **potassium line profiles.**

Ross 458C

Our spectral fits infer:
- accurate log g and Z
- overestimated $T_{\rm eff}$ (~120 K)
- underestimated R (~1.6x)

likely because models **lack clouds, reduced temperature gradient, or dis-equilibrium chemistry.**

★ Stacked Spectral-Fitting Residuals