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The Spectral ANalog of Dwarfs (SAND): New Model Atmospheres with Varying Chemistry for Galactic Archaeology with Ultracool Dwarfs

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ABSTRACT

The atmospheres of Ultracool Dwarfs (UCDs) are dominated by molecular chemistry, which makes their spectra and photometry particularly sensitive to elemental abundances. With lifespans in excess of the age of the universe, UCDs serve as chemical tracers in every component of the Milky Way. In this study, we present the Spectral ANalog of Dwarfs (SAND) grid of low-temperature model atmospheres that span $T_{\rm eff}$ from 700 K to 4000 K, $\log(g)$ from 4.0 to 6.0, [Fe/H] from −2.4 to +0.3, and a range of [α/Fe] that matches the Galactic distribution inferred from earlier spectroscopic surveys. The SAND grid primarily aims to model the spectra of brown dwarfs in the halo and thick disk of the Milky Way, and metal-poor UCDs in globular clusters.

Keywords: Brown dwarfs (185) — Stellar atmospheres (1584) — Galactic archaeology (2178)

1. INTRODUCTION

Ultracool Dwarfs (UCDs) are stars and brown dwarfs with $T_{\rm eff} \lesssim 3000$ K, masses $\lesssim 0.1 M_\odot$, and spectral classes of late-M, L, T, and Y (Kirkpatrick 2005). The strong molecular opacity in cool atmospheres makes their spectral energy distributions particularly sensitive to stellar parameters (Allard et al. 1997), allowing the determination of chemical abundances from lower resolution and lower signal-to-noise spectra than required from hotter stars. Additionally, their fully convective interiors (Burrows & Liebert 1993) and the little to no hydrogen fusion in their cores result in a distributed, largely unchanging chemical composition over cosmological timescales. Furthermore, the long-term cooling of substellar UCDs provides access to age information that can be applied to broader populations (Barrado y Navascués et al. 1999; Hsu et al. 2021). UCDs are therefore prime targets for studies of the early evolution of the Milky Way (Bochanski et al. 2007; Burgasser 2009). Globular clusters are especially suitable for this analysis, as they host the largest and oldest coeval UCD populations in the galaxy (Gerasimov et al. 2022, 2024).

Detection of UCDs is challenging since they are intrinsically faint and emit primarily in the infrared. However, deep observations with the James Webb Space Telescope and Euclid, and future observations with the Vera Rubin Observatory and Nancy Grace Roman Space Telescope are expected to uncover large numbers of these objects in all components of the Milky Way, including the Galactic halo, thick disk and globular clusters. To take full advantage of UCDs to study old stellar populations, the influence of non-solar abundances on their atmospheric chemistry and emergent spectrum must be fully accounted for. Unfortunately, there are currently few available model grids that sample the full diversity of the elemental abundances in stars in the Milky Way that extend into the UCD regime (Allard et al. 2012; Veyette et al. 2016; Gerasimov et al. 2020). In this work, we present the Spectral ANalog of Dwarfs (`SAND`) grid of low-temperature model atmospheres that aims to expand metallicity studies of UCDs.

2. MODELING

The `SAND` grid spans 700 K $\leq T_{\rm eff} \leq$ 4000 K (100 K steps), $4 \leq \log(g) \leq 6$ (in cm/s^2, 0.5 steps), and $-2.4 \leq$ [Fe/H] $\leq +0.3$ (solar scaled, variable step size). Abundance variations are parameterized through alpha enhancement, [α/Fe], with values chosen to sample the [Fe/H]-[α/Fe] distribution of

Milky Way stars inferred from APOGEE spectra (Mackereth et al. 2019). Overall, we generated 24 combinations of [Fe/H] and [α/Fe] that encompass the abundances of the Milky Way's thin disk, thick disk, and halo, as well as metal-poor α-enhanced abundances observed in globular clusters.

The `SAND` grid was calculated using the `PHOENIX` code (Hauschildt et al. 1997), version `15` (Allard et al. 2011, 2012; Gerasimov et al. 2020). Atmospheres were computed in 1D spherical geometry, and include a non-ideal equation of state (Saumon et al. 1995), non-equilibrium chemistry for selected species (Visscher et al. 2010), condensation (Allard et al. 2001), and gravitational settling of clouds (Helling et al. 2008; Allard et al. 2012). Details of our modeling framework are described in Gerasimov et al. (2022, 2024).

Obtaining fully self-consistent solutions to the atmospheric structure of UCDs is particularly challenging, as they are strongly influenced by non-equilibrium chemistry and condensate formation. In some cases, this leads to non-unique or poorly converged solutions. We visually examined synthetic photometry across multiple optical and infrared bandpasses to identify potentially unreliable models. Our final model grid contains 5181 "recommended" models that show no obvious discontinuities in the synthetic photometry, and 420 "rest" models that depart from the general trend. A small number of numerically unstable models were completely excluded from the grid.

3. RESULTS AND APPLICATIONS

Figure 1 provides a sample of the `SAND` spectra at various T_{eff} and [Fe/H]. The left panel demonstrates the growing prominence of molecular bands at lower T_{eff}, even at subsolar metallicities. The right panel explores the dependence of the spectral energy distribution on the assumed chemistry for the same temperature and gravity.

The `SAND` grid is available at an online repository[1] and Zenodo.[2] Each model is provided as a FITS file that includes the model parameters in the header, synthetic spectrum, atmospheric structure, a table of the adopted elemental abundances, and the inferred flux errors in the final solution. Synthetic

[1] https://romanger.com/models.html

[2] https://doi.org/10.5281/zenodo.10989779

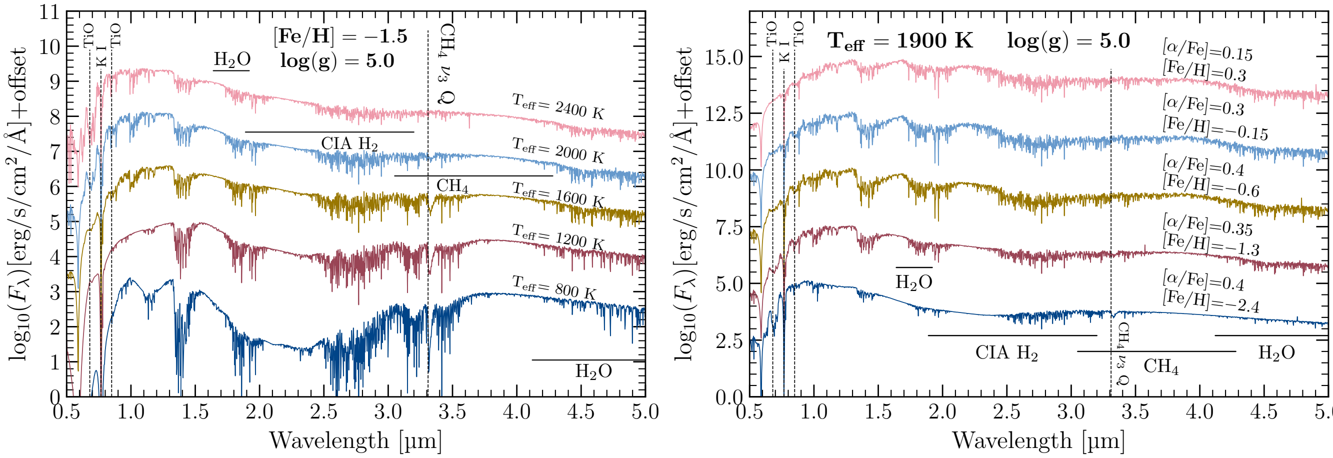

Figure 1. *Left:* `SAND` spectral sequence with $\log(g) = 5.0$, [Fe/H] $= -1.5$, [α/Fe] $= 0$, and 800 K $\leq T_{\rm eff} \leq$ 2400 K. *Right:* `SAND` spectral sequence with $T_{\rm eff} = 1900$ K, $\log(g) = 5.0$, and varying metallicity and alpha enrichment. In both panels, key molecular absorption bands (H_2O, CH_4, TiO), atomic lines of K, and the approximate wavelength range of collision-induced absorption by H_2 are highlighted. The spectra were downsampled to $R \sim 1000$ for clarity.

spectra are provided as surface flux densities per unit wavelength from 1 Å to 1 mm. The spectral resolution is adaptive with the median value of $R \sim 18\,250$ between 0.5 µm and 3 µm.

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