SEDA: Spectral Energy Distribution Analyzer for Forward Modeling and Empirical Analysis of Ultracool Objects

11 February 2026

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Summary

Brown dwarfs and extrasolar gas giant planets exhibit complex, dynamic atmospheres that undergo diverse physical and chemical processes, including disequilibrium chemistry, cloud formation, and variability, which depend on fundamental properties such as temperature, age, and metallicity (e.g., Marley and Robinson 2015). These atmospheres also exhibit a rich diversity of chemical species, including water, methane, ammonia, carbon monoxide, carbon dioxide, and silicates (e.g., Kirkpatrick 2005; Cushing et al. 2006). Studying the chemistry and physics of these atmospheres provides insights not only into the atmospheric processes that govern their behavior, but also into the formation and evolution of these objects. In the long term, understanding these atmospheric conditions is essential for characterizing potential habitable worlds with next-generation observatories and for contextualizing the uniqueness of our own.

We introduce `SEDA` (Spectral Energy Distribution Analyzer), a versatile open-source Python package for forward modeling of observations of ultracool objects, such as brown dwarfs, directly imaged exoplanets, and low-mass stars. This workflow employs a Bayesian framework based on pre-computed, self-consistent atmospheric models. `SEDA` also incorporates a broad set of empirical techniques and auxiliary tools for spectral energy distribution (SED) analysis, as described in Functionality. Overall, `SEDA` enables the inference and analysis of atmospheric composition, cloud properties, and fundamental physical parameters of ultracool objects from observational data.

Statement of Need

The James Webb Space Telescope (JWST) is revolutionizing our understanding of extrasolar atmospheres by providing high-quality observations of exoplanets and brown dwarfs. These data will synergize with observations from next-generation facilities such as the Nancy Grace Roman Space Telescope, the Habitable Worlds Observatory, the Vera C. Rubin Observatory, and 30-m class telescopes. Furthermore, a large volume of multiwavelength data is already available from wide-field photometric surveys (e.g., SDSS, York et al. 2000; and Pan-STARRS, Chambers et al. 2016), all-sky photometric surveys (e.g., Gaia, Gaia Collaboration et al. 2020; 2MASS, Skrutskie et al. 2006; and WISE, Cutri et al. 2013), targeted spectroscopic programs (e.g., SpeX Prism Library, Burgasser 2014), and both large (e.g., LAMOST, Luo et al. 2015; and APOGEE, Abdurro'uf et al. 2022) and all-sky (SPHEREx, Doré et al. 2014) spectroscopic surveys.

To fully exploit these extensive datasets, it is necessary to develop techniques and software capable of managing heterogeneous, multiwavelength observations (see Similar Tools). `SEDA` contributes to this need by providing a framework for the analysis and forward modeling of photometric and spectroscopic multiwavelength data either separately or jointly, using spectra of varying resolution and/or overlapping wavelength coverage, as well as photometry from a broad range of filter systems compiled by the Spanish Virtual Observatory (SVO) Filter Profile Service[1]. In addition to its modeling capabilities, the package incorporates a growing set of empirical techniques commonly used in the literature, offering a unified and flexible framework for both model-based and empirical SED analysis (see Functionality).

Similar Tools

Several software packages enable forward modeling of ultracool dwarf data, including `VOSA` (Bayo et al. 2008), `Starfish` (Czekala et al. 2015), `SEDkit` (Filippazzo et al. 2015), `SPLAT` (Burgasser and Splat Development Team 2017), `species` (Stolker et al. 2020), `ForMoSA` (Petrus et al. 2023), and `PICASO` (JWST Transiting Exoplanet Community Early Release Science Team et al. 2023). Except for `VOSA`, these packages primarily focus on spectroscopic data, with limited ability to incorporate photometry in the model fitting. To our knowledge, only `species` can forward model SEDs constructed from photometry alone or combined with spectra, but its empirical analysis capabilities are relatively limited. In contrast, `SPLAT` provides more empirical analysis tools similar to those in `SEDA`, but it is restricted to modeling spectroscopic observations. `SEDA` complements these packages by supporting the modeling of spectrophotometric SEDs and offering extensive empirical analysis techniques, facilitating the study of brown dwarfs and directly imaged exoplanets.

[1] https://svo2.cab.inta-csic.es/theory/fps/

Functionality

Figure 1 illustrates the core functionality and key tools of `SEDA`.

`SEDA` forward modeling employs two complementary approaches: a Bayesian framework with nested sampling to construct posterior distributions and a chi-square minimization method to find the best-fitting models (see Mathematics). The code handles both widely used and state-of-the-art atmospheric model grids, namely Lacy (2026, in preparation), Sonora Diamondback (Morley et al. 2024), Sonora Elf Owl (Mukherjee et al. 2024), Lacy and Burrows (2023), Sonora Cholla (Karalidi et al. 2021), Sonora Bobcat (Marley et al. 2021), ATMO 2020 (Phillips et al. 2020), BT-Settl (Allard et al. 2012), and Saumon and Marley (2008). Collectively, these models span a broad range of atmospheric and physical conditions, from cloud-free to cloudy atmospheres; equilibrium and non-equilibrium chemistry; temperatures from the coldest brown dwarfs through hot and temperate exoplanets to low-mass stars ($\sim$ 300–4200 K); surface gravities ($\log g$=3.0–5.5) appropriate for both young and old ultracool objects. `SEDA` also allows users to easily incorporate additional atmospheric model grids. Fitting observations to these model grids enables the inference of chemical and physical parameters defined as free parameters in the grids, along with additional quantities such as bolometric luminosity and radius, when the distance is known (see Mathematics).

Empirical analyses of SEDs include measurements of the strengths of key spectral features produced by gas and grain species using literature-defined or user-defined spectral indices, i.e., flux ratios that quantify the depth of specific spectral signatures. These indices are applied to mid-infrared features (e.g., Cushing et al. 2006; Suárez and Metchev 2022, 2023), as well as to near-infrared diagnostics designed to identify potential variable objects (e.g., Ashraf et al. 2022; Oliveros-Gomez et al. 2022, 2024). Empirical analyses also include the estimation of fundamental parameters such as bolometric luminosity and radius, and the application of published relationships between fundamental parameters, including temperature-spectral type, luminosity-spectral type, and inclination-cloudiness-color trends (e.g., Filippazzo et al. 2015; Vos et al. 2017; Kirkpatrick et al. 2021; Suárez et al. 2023).

In addition, `SEDA` provides several auxiliary tools that can be used independently, including: (*i*) the calculation of synthetic photometry from spectra for any filter available through SVO, (*ii*) a model interpolator that generates synthetic spectra for any parameter combinations within the grid coverage of available atmospheric models, (*iii*) a model examiner that enables inspection of atmospheric model properties, such as basic and free parameters, parameter coverage, resolving power, and spectral resolution, and (*iv*) access to 113 Spitzer IRS mid-infrared spectra of brown dwarfs from Suárez and Metchev (2022), along with multiple target attributes—including basic target properties, observing logs, and measured spectral indices—as listed in the tables of that work.

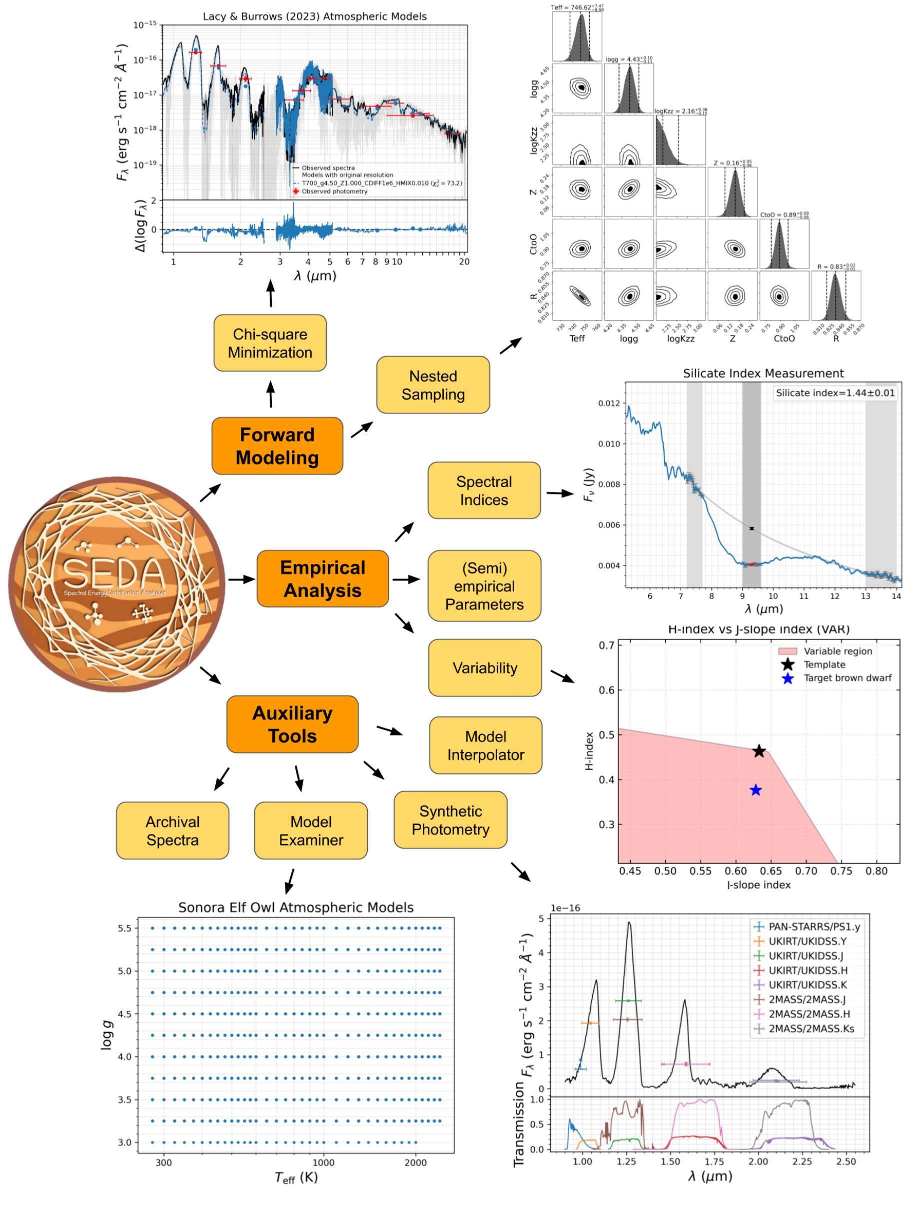

Figure 1: Overview of the SEDA workflow, illustrating key components such as forward modeling, empirical analysis, and additional useful tools.

Mathematics

For model fitting, as described in Functionality, we adopt two approaches:

1. Chi-square Minimization

The code uses the following weighted reduced chi-square (χ^2_r) definition:

$$\chi^2_r = \frac{1}{N - n_p} \sum_{i=1}^{N} w_i \left(\frac{F_{\mathrm{obs},i} - \alpha F_{\mathrm{mod},i}}{\sigma_i} \right)^2 \tag{1}$$

Here, N is the number of fitted data points, n_p is the number of free model parameters (so $N - n_p$ are the degrees of freedom), w_i is the weight assigned to each data point to balance the relative contributions of datasets with different numbers of data points, $F_{\mathrm{obs},i}$ and σ_i are the observed fluxes and their uncertainties, $F_{\mathrm{mod},i}$ are the model fluxes, and α is an unknown geometric dilution factor equal to $(R/d)^2$, where R is the object radius and d is its distance.

The code provides several options for assigning the weights w_i, which are designed to compensate for differences in the number of data points among datasets and to ensure no dataset has a negligible contribution to the fit (e.g., photometric data versus spectra, or low-resolution versus high-resolution spectra). These options include: (*i*) assigning each dataset a weight equal to the inverse of its total number of data points, so that all datasets contribute the same, even if they have very different numbers of points; and (*ii*) weighting spectroscopic data points by their wavelength resolution (i.e., wavelength step) and photometric data points by the filter effective width, such that broader filters or low-resolution spectra receive larger weights than high-resolution spectra.

To determine the value of α that minimizes χ^2_r, the code can either use the non-linear least-squares minimization python package `LMFIT` (Newville et al. 2014) or compute the analytic solution obtained by setting $\frac{\partial \chi^2_r}{\partial \alpha} = 0$, which is given by:

$$\alpha = \frac{\sum_{i=1}^{N} w_i \frac{F_{\mathrm{obs},i} F_{\mathrm{mod},i}}{\sigma_i^2}}{\sum_{i=1}^{N} w_i \frac{F_{\mathrm{mod},i}^2}{\sigma_i^2}} \tag{2}$$

2. Nested Sampling

For Bayesian model fitting, the code adopts the weighted Gaussian log-likelihood ($\ln \mathcal{L}$):

$$\ln \mathcal{L} = -\frac{1}{2} \sum_{i=1}^{N} \left[w_i \frac{(F_{\mathrm{obs},i} - \alpha F_{\mathrm{mod},i})^2}{\sigma_i^2} + \ln \left(2\pi\, \sigma_i^2\right) \right] \tag{3}$$

with all parameters defined as in Equation 1. The code wraps the model interpolator with the dynamic nested sampling package `DYNESTY` (Speagle 2020) to construct posteriors. During sampling, each generated synthetic spectrum is scaled using either $(R/d)^2$ if distance is known, or the factor that maximizes $\ln \mathcal{L}$, which is the same that minimizes χ_r^2 (Equation 2).

The scaling factor α is used to derive the radius from the equation above, independently of evolutionary models, provided that the distance is known. The observed data are complemented with the best-fitting model to construct a full hybrid SED, which is then integrated to determine the bolometric luminosity, if the distance is available.

Documentation

`SEDA` is hosted on GitHub[2] and the most up-to-date documentation is available on Read The Docs[3]. The documentation is actively maintained and provides installation instructions, an overview of the code and its principal modules, a description of the code workflow, a list of useful tools, and details on the available atmospheric models. It also includes a variety of Jupyter notebook tutorials illustrating research applications, such as forward modeling spectroscopic and/or photometric SEDs using Bayesian sampling or chi-square minimization, assembling hybrid SEDs from observations and models, measuring spectral indices, computing synthetic photometry, and inspecting atmospheric models. The API section offers a comprehensive description of all functions and classes, with basic examples provided where applicable. In addition, the documentation contains a frequently asked questions section and guidance on contributing to the code or submitting feedback.

The code also includes a suite of automated tests to verify core functionality. `SEDA` has been successfully tested with Python 3.9 or later (latest tested: Python 3.14) on Linux, Windows, and macOS.

Future Developments

`SEDA` v1.0 accompanies this publication and represents a stable, well-tested release following multiple pre-releases used for development and feedback. Among several planned additions that will further increase the functionality of the code, future releases will (i) enable measurements of projected rotational velocity ($v \sin i$) and radial velocity (RV) by incorporating rotational broadening and

[2] https://github.com/suarezgenaro/seda
[3] https://seda.readthedocs.io/

Doppler shifting into atmospheric model spectra, as well as inference of viewing geometry based on $v \sin i$, rotation period, and radius constraints (e.g., Vos et al. 2017), (*ii*) derive physical parameters such as mass, age, surface gravity, and temperature by combining atmospheric model-fitting results with evolutionary models (e.g., Suárez et al. 2021), and (*iii*) implement cross-correlation analyses to identify molecular species in medium- to high-resolution spectroscopic observations (e.g., Petit dit de la Roche et al. 2018).

We welcome feedback, suggestions, and contributions from the community to help improve `SEDA` in future releases.

Acknowledgements

The foundation of `SEDA` was introduced in Suárez et al. (2021), which featured only a chi-square minimization approach. In this work, we substantially expand upon that initial framework and release a significantly enhanced version of the software to the community. `SEDA` has already been used in at least 14 publications (including published, submitted, or in preparation works) (e.g., Suárez et al. 2025; Kiman et al. 2026; Rothermich et al. 2026; L'Heureux et al. 2026; Lam et al. 2026).

GS and JKF acknowledge funding support from JWST-GO-02124.001-A as well as NASA XRP Award 80NSSC22K0142 and NSF Award 1909776. ML and JMV acknowledge support from a Royal Society - Research Ireland University Research Fellowship (URF/1/221932, RF/ERE/221108). ML acknowledges support from Trinity College Dublin via a Trinity Research Doctoral Award.

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