



The SpeX Prism Library Analysis Toolkit (SPLAT): A Data Curation Model

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Abstract. I describe our team’s development of the SpeX Prism Library Analysis Toolkit (SPLAT), a combined spectral data repository for over 2500 low-resolution spectra of very low-mass dwarfs (late M, L and T dwarfs), and a Python-based analysis toolkit. SPLAT was constructed through a collaborative, student-centred, research-based model with high school, undergraduate and graduate students and regional K-12 science teachers. The toolkit enables spectral index analysis, classification, spectrophotometry, atmosphere model comparisons, population synthesis, and other analyses. I summarise the current components of this code, sample applications, and future development plans.

Keywords : astronomical data bases: miscellaneous — stars: low-mass, brown dwarfs — techniques: spectroscopic

1. Introduction

The spectra of the lowest-mass stars and brown dwarfs, collectively known as “ultra-cool” dwarfs (late M, L, T, and Y spectral classes), are rich in atomic and molecular diagnostics of effective temperature, surface gravity, chemical composition, cloud properties, atmospheric dynamics, and multiplicity. Several libraries of optical and infrared spectra of ultracool dwarfs are available online (e.g., IRTF Spectral Library, Rayner, Cushing & Vacca 2009; NIRSPEC Brown Dwarf Spectroscopy Survey; McLean

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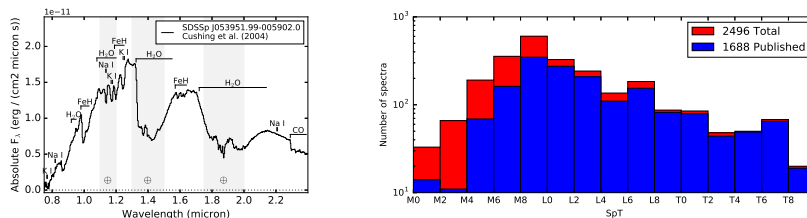


Figure 1. (Left): Example L dwarf IRTF/SpeX spectrum from SPLAT, with features labeled. (Right): Histogram of the M, L, and T dwarfs with spectra in SPLAT, separating total (2496 spectra) and published data (1688 spectra). There are ~300 spectra of other astronomical objects in the Library.

et al. 2003), and have proven useful for characterising the atmospheres of brown dwarfs and exoplanets, testing low-temperature atmospheric models, and designing filters and photometric search criteria (among other applications). However, those archives do not provide tools to conduct standard analyses of the data, such as spectrophotometry or classification, and thus require users to invest time and resources to develop those tools, and also limiting the participation of novice researchers (e.g., students, citizen scientists). Collaborative code development in astronomy, exemplified by the *astropy* python library (Robitaille et al. 2013), *dotastronomy* community, and collaborative “hack day” sessions, demonstrate a means of developing community research tools tied to data repositories, transforming them into data curation tools.

This contribution describes the SpeX Prism Library Analysis Toolkit (SPLAT), a data curation that combines a large collection of ultra-cool dwarf spectra with python-based analysis tools. In the following sections, it describes the development of the code, highlight key functionality, and identifies paths for future development. The SPLAT code can be accessed at <https://github.com/aburgasser/splat/>.

2. Development of SPLAT

SPLAT grew from the SpeX Prism Libraries (SPL; Burgasser 2014), an online repository of nearly 1000 low-resolution ($\lambda/\Delta\lambda \approx 120$), near-infrared (0.8–2.4 μm) spectra of ultracool dwarfs obtained by the community using the NASA Infrared Telescope Facility (IRTF)’s SpeX spectrograph (Rayner et al. 2003). As a large uniform dataset of ultra-cool dwarfs, the SPL has been used in over 100 studies of stars, brown dwarfs, exoplanets, and high-redshift galaxies. The SPL enables users to download both individual and sets of spectra, and provides basic visualisation; but it is a static repository with limited source information, and no tools to analyse the data files.

Starting in 2013, our group began the development of a Python-based analysis package for those data, partly to convert existing code from IDL to Python, and partly to engage students in programming and software development. The development pro-

Table 1. Modules in SPLAT.

Module	Functions
core.py	Spectrum object; combination & comparison; scaling, smoothing & reddening; indices & equivalent widths; classification
plot.py	Visualization, including batch plotting of multiple spectra
photometry.py	Spectrophotometry tools and flux/magnitude conversion
empirical.py	Conversions between spectral type and absolute magnitude, T_{eff} , luminosity, & colour; distance estimation
model.py	Interface for theoretical spectral models & model-fitting routines
evolve.py	Interface for evolutionary models and population synthesis tools
database.py	Database access and import tools; SIMBAD & VizieR through <i>astroquery</i>
citations.py	Bibliographic tools linked to BibTeX & NASA ADS
utilities.py	Program checks; conversions for coordinates, date information, & spectral types; basic statistical tools
initialize.py	Program constants

cess was designed to be collaborative, student-centred, and research-based. Analysis tools were generated through a series of quarterly exercises, steadily increasing in complexity; e.g., from “read in a spectrum and plot it” to “perform a Markov Chain Monte Carlo (MCMC) fit of a spectrum using three sets of models”. These tools were built using standard Python libraries (e.g., *numpy*, *scipy*), *astropy* routines, and other community software (e.g., *emcee*; Foreman-Mackey et al. 2013). Concurrent student-led research refined the tools through practical applications. The spectral library was also expanded to more than twice the size of SPL with new observations and contributions from the community. Source contextual data (e.g., photometry, astrometry, citations) were added, and theoretical atmosphere and evolutionary models were integrated to facilitate analysis of the data.

As of April 2017, the library contains roughly 2500 ultra-cool dwarf spectra, encompassing over 90% of known late-M, L and T dwarfs viewable from IRTF ($-50^\circ < \delta < +67^\circ$) and within 25 pc of the Sun (Figure 1). It also contains a smaller number (~ 300) of other sources, including planetary bodies (e.g., Saturn), galaxies, giant stars, white dwarfs, carbon stars, and supernovae.

3. SPLAT Tools and Components

SPLAT tools are organised into modules based on categories of analysis. The spectral data themselves are manipulated through SPLAT’s *Spectrum* class, a container for both the spectral data and associated contextual information. This class also provides baseline functions, including math operations (with robust noise propagation), wavelength and flux conversion (including $F_\nu \leftrightarrow F_\lambda$, brightness temperature, and radial velocity shifting), smoothing, scaling and reddening, and exporting of data to files. Users can work with data extracted from the SPLAT library, or upload their own spectral files. SPLAT can also “stitch” spectra covering different wavelength ranges.

Core spectral analysis tools include spectral index measurement for user-defined indices or index sets from the literature, equivalent width measurement, and com-

parison of spectra, all with Monte Carlo noise propagation and a variety of masking options. These base tools are utilised in SPLAT’s classification suite, which type ultra-cool dwarfs using indices, comparison to M0-T8 standards defined by Kirkpatrick et al. (2010), and comparison to the entire library of spectra. There is also an implementation of the Allers & Liu (2013) index-based scheme for surface gravity classification. SPLAT’s visualisation suite is designed for near-infrared spectral data, with preset feature labelling, masking of telluric bands, and visual comparison of spectra (e.g., for standard classification). There are batch plotting options for sets of spectra. SPLAT’s spectrophotometric suite contains over 100 standard (e.g., SDSS, 2MASS, MKO) and instrument-defined filters (e.g., HST/WFC3, Keck/NIRC2, Magellan/FourStar), and users can measure magnitudes, fluxes, and photon counts on AB and Vega magnitude systems, or flux-calibrate spectra to observed apparent or absolute magnitudes.

With its focus on ultracool dwarf science, SPLAT routines provide parameter conversions between spectral type and absolute magnitude, effective temperature (T_{eff}), luminosity and colour using published empirical relations. There is also a dedicated spectrophotometric distance estimator. SPLAT has tools for fitting spectra to theoretical atmosphere models, drawn from Allard, Homeier & Freytag (2012); Burrows, Sudarsky & Hubeny (2006); Madhusudhan, Burrows & Currie (2011); ?; Morley et al. (2012, 2014) and Saumon et al. (2012). The models, generally spanning $500\text{ K} \lesssim T_{eff} \lesssim 3000\text{ K}$ and with various condensate cloud treatments, are smoothed and constrained in wavelength to match the SpeX data. Low-resolution ($\lambda/\Delta\lambda = 100$), broad-band ($0.3\text{-}30\text{ }\mu\text{m}$) model spectra are also available for spectral energy distribution analysis. SPLAT provides three routines for fitting models to data using a variety of statistics, with comparisons made to both model grid points and log-linear interpolated models. There are two MCMC model fitting routines: a native implementation of the Metropolis-Hastings algorithm, and the *emcee* implementation of the affine-invariant MCMC (Foreman-Mackey et al. 2013). SPLAT also contains theoretical evolutionary models for ultra-cool dwarfs from Burrows et al. (2001); Baraffe et al. (2003) and Saumon & Marley (2008), which allow users to transform between empirical measurements of temperature, surface gravity or luminosity to the physical parameters mass, radius and age. This module also contains synthetic sample generation routines for population synthesis analysis.

SPLAT’s database routines are primarily designed for access to the internal spectral and source databases, including library searches and importing tools. Through the ‘astroquery’ package (Ginsburg et al. 2016), SPLAT provides access to VizieR and SIMBAD so users can acquire contextual data. Finally, SPLAT contains a number of utility tools that enable manipulation of bibliographic information (through BibTeX and NASA ADS queries), conversion routines for coordinates and dates, and some basic statistical tools.

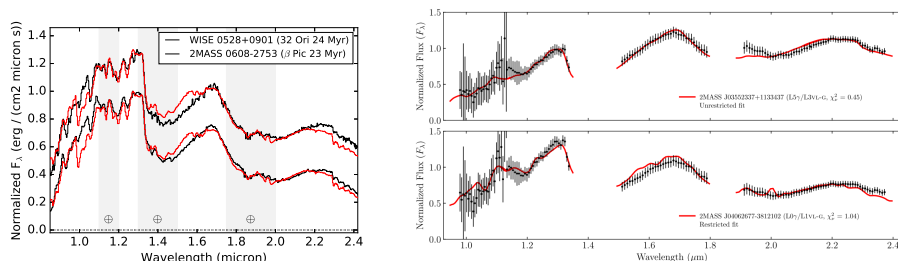


Figure 2. Examples of SPLAT in action: (Left) Spectrum of the 32 Orionis planetary-mass brown dwarf WISE J0528+0901 (top) compared to a comparably-aged member of the β Pictoris association, 2MASS J0608–2753 (bottom), and the L1 spectral standard 2MASS J2130–0845 (red overlaying both spectra). (Right) Comparison of SPLAT templates (red) 2MASS J0355+1133 (top) and 2MASS J0406–4812 (bottom) with the GPI spectrum of β Pictoris b (black points with error bars; from Chilcote et al. 2017).

4. SPLAT in Action

SPLAT has already been used in a number of studies published in the literature that examine the spectra of cool brown dwarfs and exoplanets (Figure 2). In Burgasser et al. (2016), SPLAT tools were used to identify the L dwarf WISE J0528+0901 as a young planetary-mass brown dwarf, whose kinematics place it in the 24 Myr-old 32 Orionis association. In Aganze et al. (2016), SPLAT tools were used to both classify and measure the metallicity of the very low-mass secondary in the GJ 660.1 system through spectral model fits. In Gillon et al. (2016), SPLAT tools were used to determine the metallicity of the planet-host star TRAPPIST-1 using equivalent width measurements and empirical calibrations. In De Rosa et al. (2016); Chilcote et al. (2017), and Johnson-Groh et al. (2017), SPLAT tools were used to characterise Gemini Planet Imager (GPI; Macintosh et al. 2014) spectra of the directly-imaged exoplanets HD 95086b, β Pictoris b and HD 984B, respectively

5. Future Directions

With fewer than 3000 spectra and an equivalent number of models, SPLAT is not a “big data” resource, so there is interest in expanding the library and toolkit for use with data from other infrared spectrographs (e.g., SpeX cross-dispersed mode, APOGEE, Magellan/FIRE, VLT/X-shooter, various/TripleSpec) and from optical spectrographs (e.g., SDSS). While we have demonstrated SPLAT’s use for high resolution data (Gillon et al. 2016), a broader expansion will require generalising the Spectrum class and many of the analysis routines to those other data formats. Replacement of the Spectrum class is likely to be imminent, as *astropy* has recently begun the process

of integrating spectral analysis tools into its base-code (`specutils`¹), to which our team aims to contribute SPLAT tools. It is also desirably to expand SPLAT’s scientific applications beyond ultra-cool dwarfs, e.g., to planetary bodies (e.g., asteroidal surface composition modelling), exoplanets (e.g., transmission spectroscopy), and galaxies (e.g., population synthesis modelling); as well as mission-specific tool development (e.g., HST/WFC3; Euclid). We are also developing a web portal for SPLAT tools which will allow users without formal Python/programming backgrounds to explore these data, a task well-suited for K-12 education and citizen science research.

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¹<https://github.com/astropy/specutils>