Jointly Modeling Telluric Features and Stellar Variability with Stellar Spectra Observation Fitting

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Recently, several extreme precision radial velocity (EPRV) spectrographs have been providing high-resolution and high signal-to-noise spectra with the express purpose of exoplanet discovery and characterization. A significant barrier to this endeavor is the existence of time-variable features in the spectra from both telluric absorption and stellar variability. Traditional methods discard significant portions of data to minimize the effects of telluric contamination. Reaching Earth analogs could require reducing effects of contamination from more and more microtellurics and thus discarding an ever increasing fraction of the spectrum, but new data-driven methods may enable the use of a larger fraction of the available data. While there exist methods for modeling out the telluric features (e.g. Bedell et al. 2019) or the stellar variability (e.g. Gilbertson et al. 2020) individually, there is a need for new tools that are capable of modeling them simultaneously. Here we present StellarSpectraObservationFitting.jl (SSOF), a Julia package for creating data-driven models (with fast, physically-motivated Gaussian Process priors) for the time-variable spectral features in both the observer and observed frames. SSOF outputs estimates for the radial velocities, template spectra in both the observer and barycentric frames, and scores and feature vectors that quantify the shapes and amplitudes for the temporal variability of time-variable telluric and stellar features, while accounting for the wavelength-dependent instrumental line-spread function. We have demonstrated SSOF's state-of-the-art RV precision performance on NEID data (increasing measurement precision by 2-5x over the CCF-based data reduction pipeline) and discuss how the resulting model can be used to aid in mitigating remaining sources of correlated noise in the radial velocity time series.

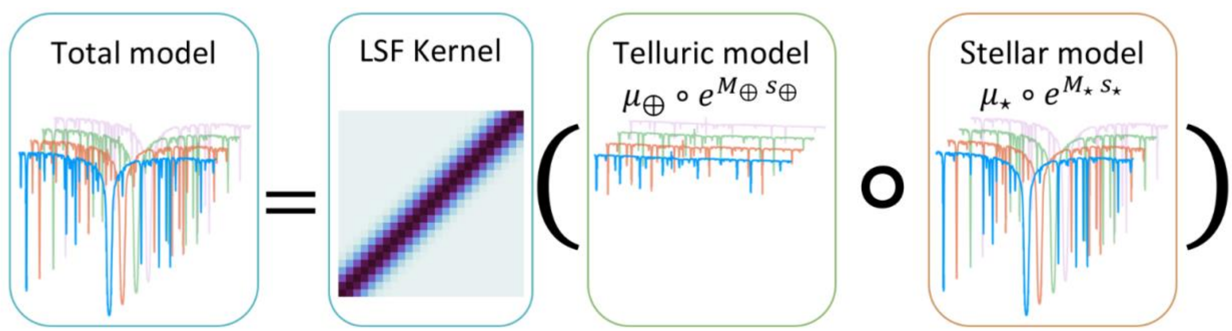

Figure 1: The SSOF models are created by element-wise multiplying linear models for the telluric and stellar spectra and then multiplying by an instrumental LSF kernel. This flexibility is instrument-agnostic, and results in a robust, automated separation of telluric and stellar components

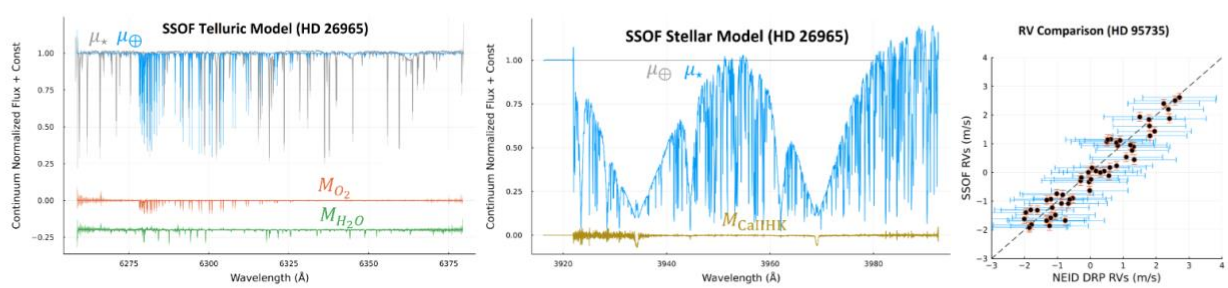

Figure 2: Some illustrative SSOF outputs, derived using only EPRV spectra. Left: SSOF can separate the different time-variable effects of oxygen and water telluric features (seen in the first two bases). Middle: Example of SSOF automatically identifying the CaII H and K line core emission variations. Right: SSOF 's RVs (when combining information from multiple orders) are 2-5$\times$ better precision (orange error bars) and lower RMS scatter than the outputs of NEID's CCF-based DRP (blue error bars)