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Stellar and Exoplanetary Atmospheres Bayesian Analysis Simultaneous Spectroscopy

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Abstract

We present the results of Stellar and Exoplanetary Atmospheres Bayesian Analysis Simultaneous Spectroscopy (SEA BASS) for several systems. SEA BASS is a scheme that enables simultaneous derivation of four-coefficient stellar limb-darkening profiles, transit depths and orbital parameters from exoplanetary transits at multiple wavelengths. The fully empirical approach is recommended to avoid potential biases in transit depth due to the use of limb-darkening coefficients obtained from stellar-atmosphere models. We show that, in some cases, inaccurate limb-darkening parameterisations and/or orbital parameters may impart trends on the derived exoplanetary spectra, therefore leading to erroneous characterisation of the exoplanet atmospheres. We discuss how to minimise the parameter degeneracies that otherwise would significantly inflate the error bars or prevent the convergence of the fit. Finally, we assess the reliability and accuracy of state-of-the-art stellar-atmosphere models for describing the limb-darkening profiles of a range of stellar types.

1. Introduction

Characterisation of the atmospheres of transiting exoplanets relies on accurate measurements of the extent of the optically thick area of the planet at multiple wavelengths with a precision $\lesssim$100 parts per million (ppm). Next-generation instruments onboard the James Webb Space Telescope (JWST) are expected to achieve $\sim$10 ppm precision for several tens of targets. A similar precision can be obtained in modeling only if other astrophysical effects, including the stellar limb-darkening (the radial decrease in specific intensity), are properly accounted for. Stellar-atmosphere models are commonly used to predict the limb-darkening profiles, but empirical estimates are desirable, both to test the stellar models and to reduce potential biases in transit depths due to errors in the theoretical models or to other second-order effects, such as stellar activity, granulation, gravity darkening, etc. Numerous functional forms, so-called limb-darkening laws, have been proposed in the literature to approximate the stellar intensity profile with different numbers of coefficients. While some two-coefficient laws are appropriate for certain stellar types and passbands [Espinoza & Jordan 2016, Morello et al. 2017, Maxted 2018], the Claret's four-coefficients formula is the most robust over all stellar types and passbands [Claret 2000, Morello et al. 2017].

2. The method

The SEA BASS method consists of measuring the "geometric" orbital parameters from infrared transit observations, then implementing the results as informative priors when model-fitting at shorter wavelengths. The impact parameter, b, and central transit duration, T_0, constitute an equivalent set of less correlated parameters than the semi-major axis in units of stellar radius, a/R_*, and inclination, i. The SEA BASS approach is motivated by the smaller limb-darkening effect in the infrared, which mitigates the potential biases due to inaccurate models, and the negligible wavelength-dependence of a/R_* and i. Different variants of the original algorithm, such as using multiple infrared passbands with fixed (four) or free (two) limb-darkening coefficients to derive the geometric priors, will be discussed.

3. Results

3.1. Synthetic datasets

Figure 1 show the results in transit depth of the SEA BASS fit (and others) on synthetic datasets [Morello et al. 2017]. The use of informative priors on a/R_* and i is necessary to enable convergence of the fit with free four-coefficient limb-darkening; the resulting error bars are smaller than those obtained with free two-coefficient limb-darkening and uniform priors on a/R_* and i.

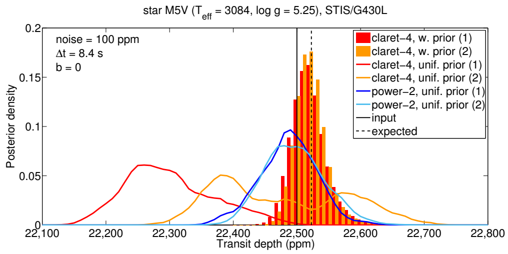

Figure 1: Histograms (red and orange channels) of the MCMC-sampled posterior distributions of the transit depth for a hot-Jupiter in front of a M5 dwarf, *Hubble* STIS/G430L passband, fitting R_p/R_*, a/R_*, i, claret-4 limb-darkening coefficients and the normalization factor, adopting gaussian priors on a/R_* and i. The histogram channels are half-thick and shifted to improve their visualization. The red and orange lines denotes the analogous posterior distributions with non-informative priors for all parameters (the shape and the discrepant results indicate that the chains did not converge, in this case). The blue and light-blue lines are for the case of power-2 limb-darkening and non-informative priors for all parameters.

3.2. Real datasets

Figure 2 compares the empirical limb-darkening profiles obtained for HD209458 over five *HST*/STIS passbands in the range 290–570 nm with some reference models [Morello 2018]. The discrepancies are significant for the three passbands with the highest Signal-to-Noise Ratio (SNR). Figure 3 compares the relevant exoplanet transmission spectra. In this case, no significant biases are obtained when using fixed limb-darkening coefficients from stellar-atmosphere models. However, HD209458 is relatively well-known, because it is a Sun-like star. The preliminary analyses on other systems present larger effects in the exoplanet transmission spectra.

4. Conclusions

We performed self-consistent analyses of infrared to visible exoplanetary transits to obtain accurate transmission spectra of the exoplanet atmospheres and stellar limb-darkening profiles (SEA BASS). The new method is necessary to avoid the potential biases introduced by the stellar-atmosphere models, which, in some cases, may significantly alter the exoplanet spectra. We also assess the reliability and accuracy of state-of-the-art stellar-atmosphere models for describing the limb-darkening profiles of a range of stellar types.

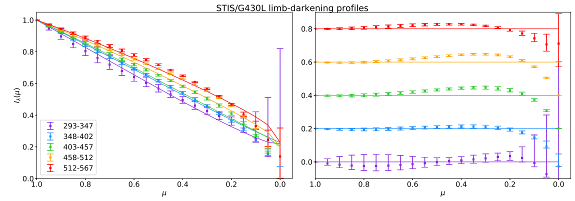

Figure 2: Left panel: empirical limb-darkening profiles obtained from the spectral lightcurve fits (differently coloured squares) and theoretical models computed by [Knutson et al. 2007] (same color lines). Right panels: residuals between the empirical and theoretical profile with vertical offsets.

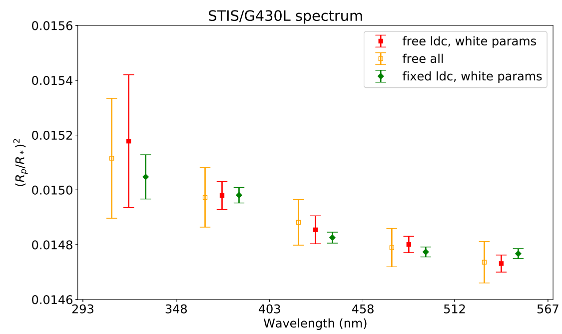

Figure 3: Transit depths for five spectral bins, using: b and T_0 fixed to the Spitzer/IRAC weighted mean values, phase shifts obtained from the white lightcurve fit, and free limb-darkening cofficients (red, full squares), or fixed limb-darkening coefficients reported by [Knutson et al. 2007] (green diamonds), all free parameters with Spitzer/IRAC weighted mean priors on b and T_0 (orange, empty squares).

Acknowledgements

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