EPSC Abstracts
Vol. 11, EPSC2017-120, 2017
European Planetary Science Congress 2017

High-precision stellar limb-darkening in exoplanetary transits

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Abstract

Characterization 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 modelling only if other astrophysical effects, including the stellar limb-darkening, are accounted for properly. Here, we

1. explore the limits on precision due to the mathematical formulas currently adopted to approximate the stellar limb-darkening, and to the use of limb-darkening coefficients obtained either from stellar-atmosphere models or empirically;

2. propose a new limb-darkening law with two coefficients, 'power-2', which outperforms other two-coefficient laws adopted in the literature in most cases, and particularly for cool stars;

3. demonstrate an optimal strategy to fitting for the four-coefficients limb-darkening in the visible, using prior information on the exoplanet orbital parameters to break some of the degeneracies that otherwise would prevent the convergence of the fit.

Infrared observations taken with the JWST will provide accurate measurements of the exoplanet orbital parameters with unprecedented precision, which can be used as priors to improve the stellar limb-darkening characterization, and therefore the inferred exoplanet parameters, from observations in the visible, such as those taken with Kepler/K2, JWST, other past and future instruments. The novel approach, proposed here, could solve some of the controversial results reported in the literature, which relies on empirical estimates of quadratic limb-darkening coefficients.

1. Introduction

Exoplanetary transits are revealed through periodic drops in the stellar flux, due to the partial occultation of the stellar disk by the planet for a portion of its orbit. The amplitude of the flux decrement is primarily determined by the size of the planet relative to the star, but also depends on the location of the occulted area of the stellar disk and the wavelength observed, because of stellar limb-darkening (the radial decrease in specific intensity). Accurate modeling is paramount to achieve the 10–100 ppm precision, required for spectroscopic studies of the exoplanet atmospheres.
Numerous functional forms to approximate limb-darkening have been proposed in the literature (see [Howarth 2011] for a review). In exoplanetary studies, the limb-darkening coefficients for a given 'law' are often fixed to best-fit values on the model intensities. 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.

2. Simulations

In order to investigate the consequences of various approximations to limb-darkening, we calculated 'exact' synthetic transit photometry as a reference, using PHOENIX model-atmosphere intensities [Allard et al. 2012], coupled to an accurate numerical integration scheme for the light-curves. We model-fitted the exact light-curves either using fixed limb-darkening coefficients inferred from the model intensities or including them as free parameters in the fit.

2.1. Intensity distributions: plane-parallel vs. spherical

In the literature, most stellar-atmosphere models are plane-parallel, but this geometry may introduce a bias, depending on the extent of the optically thin layers. In spherical models, the μ values depend on the rather arbitrary definition of the stellar radius. Furthermore, the rapid changes in $I_\lambda(\mu)$ that arise at small μ in the spherical models (see Fig. 1) are, inevitably, not well approximated by any standard parametric law.

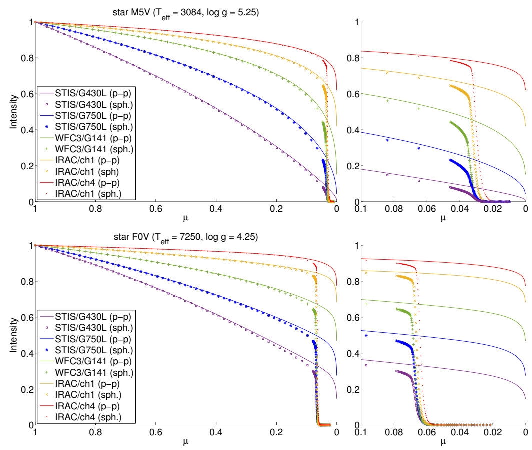

Figure 1: Angular intensity distributions for M5 and F0 dwarfs, using plane-parallel and spherical geometry, integrated over different instrument passbands.

2.2. Tests on limb-darkening laws and proposed method

We analyzed the precision with which different limb-darkening laws describe the intensity profile and the transit morphology, and derive the correct transit depth. The new ‘power-2’ law [Morello et al. 2017] outperforms other two-coefficient laws adopted in the literature in most cases, and particularly for cool stars. Two-coefficient laws are typically used to obtain empirical estimates, as parameter degeneracies hamper convergence when fitting higher-order models. Unfortunately, all the two-coefficients laws are biased for some stellar types and wavelengths, but most of them are sufficiently accurate in the infrared wavelengths. The four-coefficients formula [Claret 2000], hereinafter ‘claret-4’, is the most robust one over all spectral types and passbands, enabling an absolute precision of $\lesssim$30 ppm in transit depth for a hot Jupiter. Our proposal is that, if the geometric parameters, a_R (semi-major axis in units of the stellar radius) and i (orbital inclination), are measured in the infrared, the results can be implemented as an informative prior when fitting at shorter wavelengths. The use of gaussian priors on a_R and i enables convergence of the MCMC fits with claret-4 coefficients (see Fig. 2).

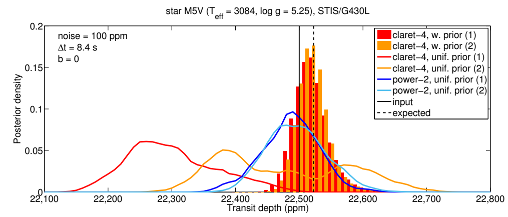

Figure 2: Histograms (red and orange channels) of the MCMC-sampled posterior distributions of the transit depth for a hot-Jupiter in front of a M5 dwarf, *Hubble* STIS/G430L passband, fitting p, a_R, i, claret-4 limb-darkening coefficients and the normalization factor, adopting gaussian priors on a_R 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. Summary and conclusions

We studied the potential biases in transit depth due to the use of theoretical stellar limb-darkening coefficients obtained from plane-parallel model atmospheres, and when fitting for empirical limb-darkening coefficients, over a range of model temperatures and instrumental passbands. Our results indicate that an absolute precision of $\lesssim$30 ppm can be achieved in the modelled transit depth at visible and infrared wavelegths, depending on the stellar type, if adopting the claret-4 law.

We developed an optimal strategy to fitting for the claret-4 limb-darkening coefficients in the UV and visible light-curves, using prior information on the exoplanet orbital parameters to break some of the degeneracies. The forthcoming JWST mission will provide accurate information on the orbital parameters of transiting exoplanets through observations performed by MIRI, enabling wide application of the approach discussed in this talk.

Acknowledgements

G. Morello is supported by the ERC projects ExoLights (617119).

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