Exoplanets 5

Treatment of limb darkening in exoplanet atmospheric retrieval algorithms

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Motivation

Stellar limb darkening affects the retrieval of exoplanet transmission spectra, which are the wavelength-dependent planetary radii, from spectroscopic transit light curves. The standard approach to address limb darkening involves approximating it using various laws and empirically determining these laws' coefficients during retrievals. Here we test how accurately three common laws can reproduce stellar limb darkening at different wavelengths.

Limb darkening and laws

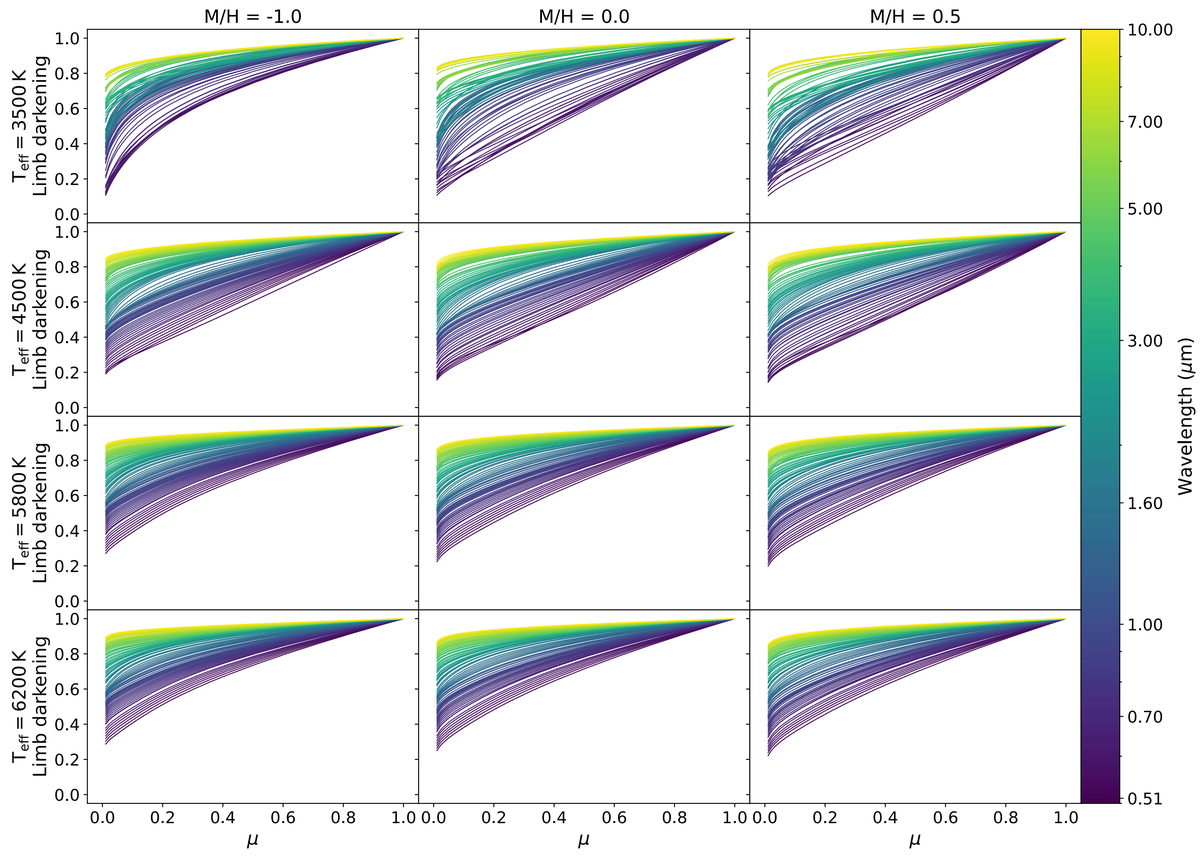


Fig. 1. Stellar limb darkening curves ($I_\lambda(\mu)$ / $I_\lambda(\mu = 1)$) at different wavelengths derived from the MPS-ATLAS spectral library (Kostogryz et al. 2023).

Limb darkening curves come in a great variety of shapes (Fig. 1).

Question to answer: can we describe all of them by a simple law without introducing spurious features in retrieved transmission spectra?

We test:

Quadratic law

$$\frac{I_\lambda(\mu)}{I_\lambda(\mu = 1)} = 1 - u_1 (1 - \mu) - u_2 (1 - \mu)^2$$

Power law

$$\frac{I_\lambda(\mu)}{I_\lambda(\mu = 1)} = 1 - c(1 - \mu^\alpha)$$

Three-parameter law

$$\frac{I_\lambda(\mu)}{I_\lambda(\mu = 1)} = 1 - c_2(1 - \mu) - c_3\left(1 - \mu^{\frac{3}{2}}\right) - c_4(1 - \mu^2)$$

Effects on planetary spectra

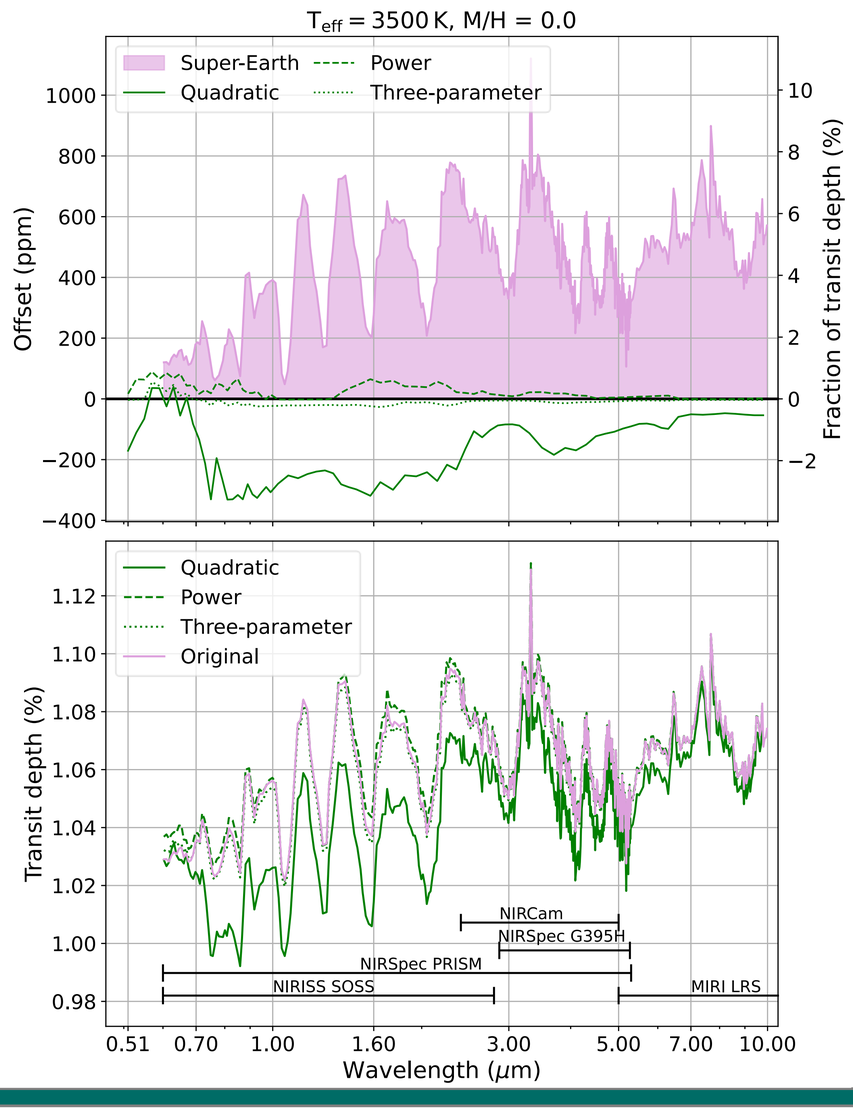
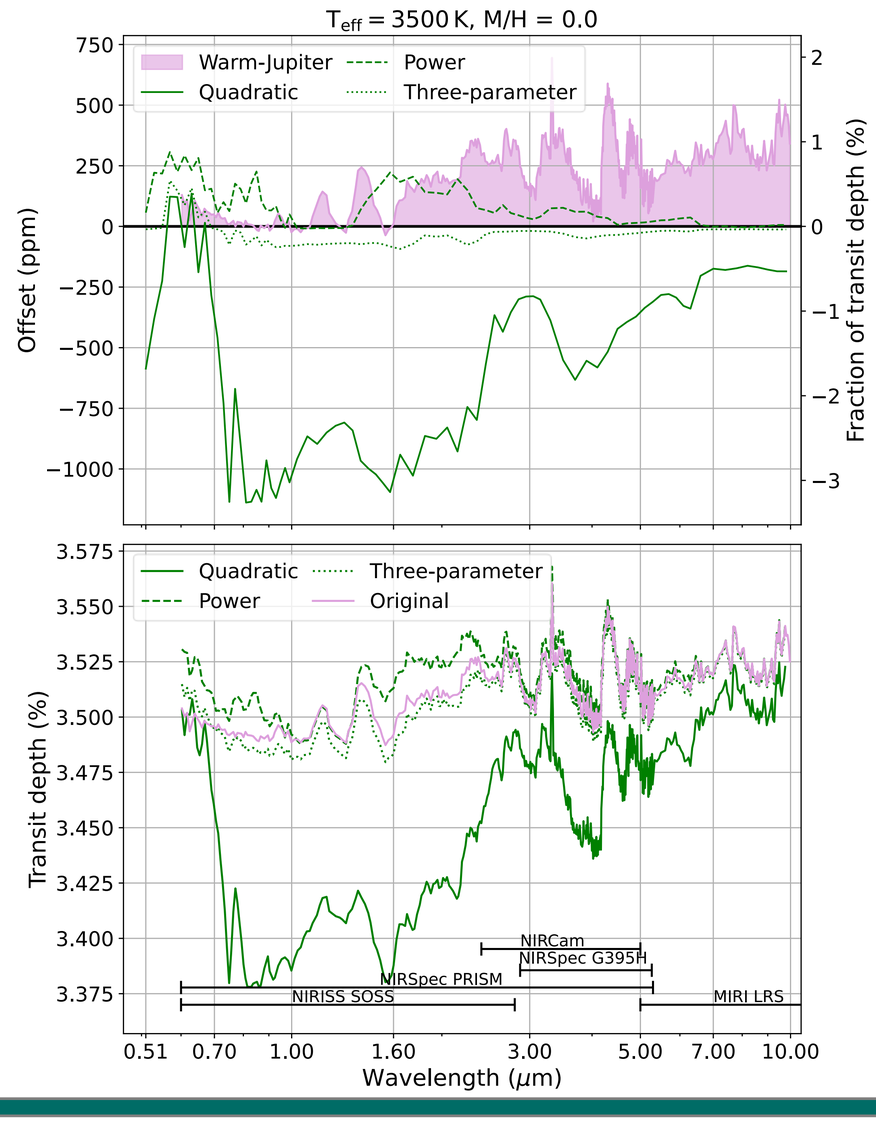


Fig.2. Representative cases of super-Earth (left) and warm Jupiter (right) transiting an M dwarf at at $b = 0.7$. Top: Offsets from true transit depth retrieved with three different limb darkening laws, compared to a simulated spectrum of a super-Earth, from Niraula et al. (2022). Bottom: Spectrum of a super-Earth (left) and warm-Jupiter (right) compared to themselves when the limb darkening induced offsets are applied.



Main findings and recommendations

- The use of the quadratic law can introduce significant biases and features into retrieved exoplanet transit spectra. As such we do not recommend its use in exoplanet transit retrievals;
- When processing transits observed at long wavelengths (> 5 μm) use of the power law still produces acceptable results with very small offsets;
- At shorter wavelengths (< 5 μm) and high impact parameters (b>0.5), the retrievals using the power law also become severely biased. For such cases, if not for all, the three-parameter law should be used.