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Towards Mitigating the Impact of Stellar Photospheric Heterogeneity on Precise Exoplanet Transmission Spectra

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Abstract

Exoplanet transmission spectroscopy, the study of spectroscopic transit depths, provides our best opportunity to characterize the atmospheres of temperate, Earth-sized exoplanets in the next two decades. However, this technique is subject to spurious signals introduced by the photospheric heterogeneity of exoplanet host stars, which may mimic or mask real exoplanetary signals. As the late-type hosts that provide the most favorable planet-to-star radius ratios for studying small exoplanets also tend to be more photospherically heterogeneous, our ability to disentangle stellar and planetary signals represents a possible limitation for precise transmission spectroscopy.

Here we present our recent work to understand the scale of TLS signals with forward models and to characterize the photospheres of important exoplanet host stars through (1) transit crossings of magnetic active regions, (2) joint retrievals of stellar and exoplanetary properties from transmission spectra, and (3) stellar photospheric decomposition with moderate-resolution visual and near-infrared spectra. Constraining the photospheric heterogeneity of exciting exoplanet host stars with these approaches will be key to realizing the opportunity to characterize Earth-sized exoplanets via transits.

1. Introduction

Transiting exoplanets offer a unique opportunity to study the atmospheres of temperate Earth-sized planets in other systems with current and near-future facilities [1, 2]. By absorbing and scattering starlight, exoplanet atmospheres produce spectroscopic transit depth variations that allow us to probe their physical structures and chemical compositions [9]. Studies of spectroscopic transit depths, or transmission spectra, have yielded detections of atomic and molecular absorption [10], which in turn place constraints on the atmospheric pressure-temperature profiles [4]. With JWST and the ground-based extremely large telescopes, the coming decade promises a revolution in the studies of exoplanetary atmospheres, particularly those of temperate, Earth-sized exoplanets. For the first time in human history, we will have the technological capability to detect biosignatures in exoplanetary atmospheres, given the right targets and provided we can disentangle these minute signals from other astrophysical signals.

2. The Transit Light Source Effect

In the context of transits, the most salient astrophysical signals result from the transit light source (TLS) effect (Figure 1). This effect imprints on transit depths the contrast between the emergent spectrum of the transit chord—the actual light source for the transmission measurement—and the out-of-transit full-disk stellar spectrum—the necessarily assumed light source. Thus, the photospheric heterogeneity of an exoplanet host star produces apparent spectroscopic transit depth variations that can mimic or mask those produced by the exoplanetary atmosphere. Recent modeling efforts [7, 8] and increasingly precise observations [6, 11] are revealing that our understanding of transmission spectra of the smallest transiting exoplanets will likely be limited by our knowledge of host star photospheres. Therefore, successfully leveraging the transit opportunity to probe the atmospheres of temperate, terrestrial exoplanets will require precise constraints on host star photospheric properties.

3. Promising Mitigation Strategies

Here we share recent results that illustrate promising approaches for characterizing stellar photospheres and informing interpretations of transmission spectra of

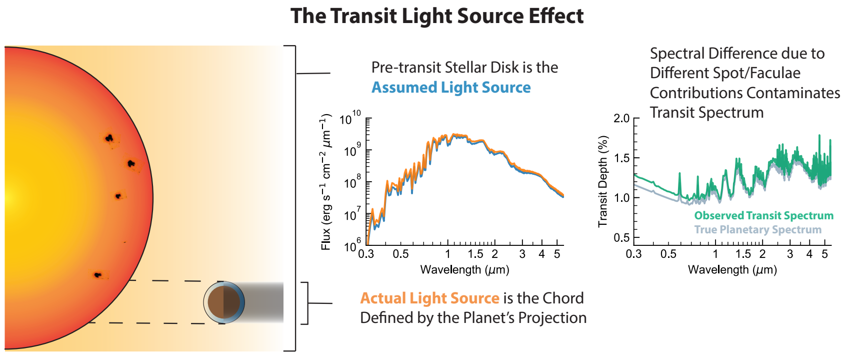

Figure 1: Schematic of the transit light source (TLS) effect. The heterogeneity of a stellar photosphere introduces a spectral difference between the light that illuminates the exoplanetary atmosphere during a transit and the disk-integrated stellar spectrum, which provides the reference for measuring transit depths. This spectral mismatch produces apparent transit depth variations that can mimic or mask exoplanetary atmospheric features. From [7].

the smallest exoplanets. First, we present our recent work to understand the scale of TLS signals in exoplanet transmission spectra through forward models [7, 8]. Our results show that TLS signals can be comparable to or larger than terrestrial exoplanetary atmospheric signals for K- and M-dwarf systems in general. For a given system, the scale of the TLS signals will be governed by the specific photospheric parameters, including the principal emergent spectra present, their covering fractions, and their spatial distributions.

In this context, we also discuss our recent and ongoing work to characterize the photospheres of exoplanet hosts through: (1) transit crossings of magnetic active regions [3]; (2) joint retrievals of stellar and exoplanetary properties from transmission spectra [5, 3]; and (3) stellar photospheric decomposition with moderate-resolution visual and near-infrared spectra. These approaches each provide useful constraints on the number of primary spectral components present in the photosphere (e.g., spots, faculae, and quiescent photosphere), their spectra, and covering fractions.

4. Summary and Conclusions

Our forward models show that TLS signals are considerable in transmission spectra from K- and M-dwarf systems. As efforts to characterize the atmospheres of temperate, terrestrial planets in the near-term future will be limited to these systems, constraining photospheric heterogeneity is crucial for disentangling stellar and planetary signals in precise transmission spectra. Fortunately, promising approaches exist for doing so, such as those presented here; their further development will be key to realizing the transit opportunity to characterize temperate Earth-sized planets.

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