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The effects of stellar variability on transit spectroscopy observations in the ARIEL space mission examined using the ExoSim simulator

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Abstract

ExoSim is an end-to-end transit spectroscopy simulator that has been used in the phase A study of ARIEL (an ESA M4 candidate). Here we use ExoSim to explore the effects of stellar variability on observations by ARIEL.

1. Introduction

Stellar variability has been a recognized problem in transit spectroscopy observations for some years, affecting the precision and accuracy of transit depth measurements. Pulsations and granulation can cause fluctuations of the order of seconds to minutes, and represent a source of astrophysical noise. Stellar activity through the presence of star spots can have at least 2 major effects (Ballerini et al, 2012). Unocculted spots can reduce the apparent radius of the star leading to over-estimation of the fractional transit depth. Occulted spots can distort the light curve, causing an upward "bump", leading to under-estimation of the transit depth when fitting a standard light curve model.

2. ExoSim

ExoSim is a generic time domain simulator which is unique in its versatility of application for exploring signal and noise issues in exoplanet transit spectroscopy (Sarkar et al, 2016). ExoSim models both the astrophysical scene and the optical system (Figure 1). It can simulate primary and secondary transit as well as phase curves. ExoSim models the telescope, multiple instrument channels and detector(s). Since ExoSim performs a time domain simulation, it is particularly suited for capturing the effects of correlated noise (e.g. from pointing jitter or stellar variability) and time-dependent systematics. ExoSim outputs image files akin to a 'real' observation and thus requires a data reduction pipeline to extract the required signal and noise information or reconstruct the planet spectrum. ExoSim can examine both the out-of-transit noise as well as simulate full transits and obtain the uncertainty on the planet spectrum. ExoSim has been extensively validated and can be applied to any telescope/instrument capable of transit spectroscopy.

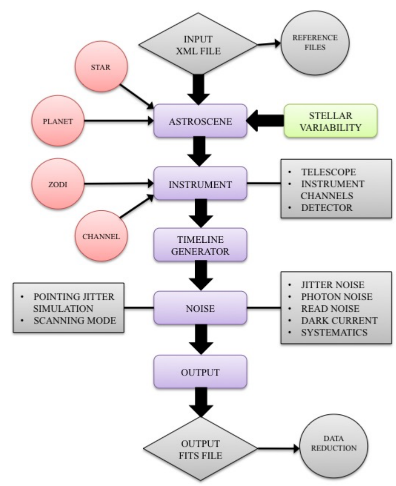

Figure 1: ExoSim - a generic time domain simulator of transit spectroscopy observations. Shown is the modular (and upgradeable) architecture and informational flow. By exchanging the input XML-based file and associated reference files, different telescopes and instrument configurations can be applied to the same generic shell.

3. Pulsations and Granulation

A stellar convection model was developed at KU Leuven and used to obtain timelines of wavelength-dependent flux variations caused by granulation and pulsations on different stellar types. These timelines were incorporated into ExoSim simulations of ARIEL observations of the exoplanet host stars GJ1214 (a dim target for ARIEL) and HD209458 (a bright target for ARIEL), observed out-of-transit. Each ARIEL channel was simulated: AIRS Ch1 (3.9-7.8 μm), AIRS Ch0 (1.95-3.9 μm), NIRSpec (1.25-1.95 μm), and three photometric channels: FGS1, FGS2 and VISPhot (0.5, 0.9 and 1.1 μm respectively). The noise variance per unit time per spectral resolving element-sized bin was obtained, and compared to the noise from other noise sources simulated individually. We find that the noise from stellar convection is very small compared to other noise sources and not significant compared to the photon noise (Table 1).

Table 1: Stellar convection noise variance as a percent of photon noise variance. Median values are given for spectroscopic channels.

Channel	GJ1214	HD209458
AIRS Ch1	0.004	0.002
AIRS Ch0	0.014	0.002
NIRSpec	0.098	0.011
FGS2	0.449	0.120
FGS1	0.380	0.104
VISPhot	0.078	0.708

4. Star spots

A star spot model was developed which simulates cold spots and hot faculae distributed over a stellar surface transited by a planet (Figure 2). The spot coverage can be selected as well as the temperature contrast of spots and faculae. A log-normal distribution is used for the spot sizes (Solanki & Unruh, 2004), which are randomly allocated. The spatial distribution can be random uniform or centred at a particular latitude. This model was incorporated into ExoSim, and transit simulations performed with the ARIEL model. With this setup we performed Monte Carlo simulations for exoplanets at different spot coverages, randomly changing the distribution of spots in each realization. An example is shown in Figure 3. The wavelength-dependent bias varies with each realization giving a distribution of transit depths per wavelength bin which serves as a measure of uncertainty for any single observation. Averaging repeated measurements should tend to mitigate the effects of bias as well as its wavelength-dependent variation. We will use these ExoSim simulations to quantify the effects of star spots on ARIEL targets, and as a test bed for optimal decorrelation strategies (e.g Micela, 2015 and Waldmann et al, 2013).

5. Summary and Conclusions

We have used ExoSim to examine the noise from stellar variability and activity for the ARIEL space mission. We have shown that pulsations and granulations

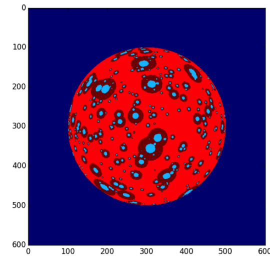

Figure 2: ExoSim star spot simulator example.

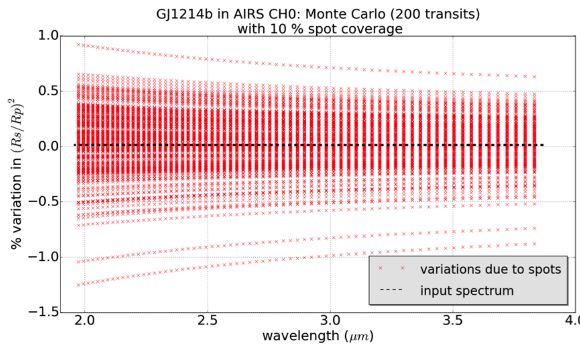

Figure 3: Monte Carlo simulation in ExoSim for Ch0 (200 realizations) showing the distribution in wavelength-dependent bias due to spots. Bias can be above or below true spectrum depending on the effect of spots in any one case.

do not represent a significant noise source compared to photon noise. We have shown the capability of the ExoSim star spot model to produce transit depth distributions for reconstructed exoplanet transmission spectra from which the uncertainty due to spots can be inferred and assessed, and with which, if required, decorrelation methods can be tested for efficacy.

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