EPSC Abstracts
Vol. 10, EPSC2015-853, 2015
European Planetary Science Congress 2015

Revisiting Spitzer Transit Observations with Independent Component Analysis: New Results for Exoplanetary Systems

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Abstract

Blind source separation techniques are used to reanalyse several exoplanetary transit lightcurves of a few exoplanets recorded with the infrared camera IRAC on board the Spitzer Space Telescope during the “cold” era. These observations, together with observations at other IR wavelengths, are crucial to characterise the atmospheres of the planets. Previous analyses of the same datasets reported discrepant results, hence the necessity of the reanalyses. The method we used here is based on the Independent Component Analysis (ICA) statistical technique, which ensures a high degree of objectivity. The use of ICA to detrend single photometric observations in a self-consistent way is novel in the literature. The advantage of our reanalyses over previous work is that we do not have to make any assumptions on the structure of the unknown instrumental systematics. We obtained for the first time coherent and repeatable results over different epochs for the exoplanets HD189733b and GJ436b [Morello et al.(2014), Morello et al.(2015)]. The technique has been also tested on simulated datasets with different instrument properties, proving its validity in a more general context [Morello et al.(2015b)]. We will present here the technique, and the results of its application to different observations, in addition to the already published ones. A uniform re-analysis of other archive data with this technique will provide improved parameters for a list of exoplanets, and in particular some other results debated in the literature.

1. Introduction

Observations of exoplanetary transits are a powerful tool to investigate the nature of planets around other stars. Transits are revealed through periodic drops in the apparent stellar brightness, due to the interposition of a planet between the star and the observer. The shape of an exoplanetary transit lightcurve depends on the geometry of the star-planet-observer system and the spatial distribution of the stellar emission at the wavelength at which observations are taken [Mandel & Agol(2002)]. Multiwavelength transit observations can be used to characterise the atmospheres of exoplanets, through differences in the transit depths, typically at the level of one part in $\sim 10^4$ in stellar flux for giant planets [Brown(2001)]. For this purpose, the diagnostic parameter is the wavelength-dependent factor $p = r_p/R_s$, i.e. the ratio between the planetary and the stellar radii (or p^2, so-called transit depth).

The exoplanet HD189733b is one of the most extensively studied hot Jupiters: the brightness of its star allows spectroscopic characterisation of the planet’s atmosphere. Different analyses of the same dataset, including two simultaneous Spitzer/IRAC observations at 3.6μm and 5.8μm, have been used to infer the presence of water vapour in the atmosphere of HD189733b [Beaulieu et al.(2008), Tinetti et al.(2007)], or to reject this hypothesis [Désert et al.(2009)]. GJ436b is a Neptune-sized planet for which the atmospheric composition is very debated in the literature [Stevenson et al.(2010), Beaulieu et al.(2011), Knutson et al.(2011), Knutson et al.(2014)]. Some authors also claimed that stellar variability may affect the observed spectra at a level that it would be impossible to infer any atmospheric properties.

Although stellar activity may significantly affect estimates of exoplanetary parameters from transit lightcurves [Ballerini et al.(2012), Berta et al.(2011)], the method used to retrieve the signal of the planet also plays a critical role. The analyses mentioned above were all based on parametric corrections of the instrumental systematics, and are thus, to some degree, subjective. Recently, non-parametric methods have been proposed to decorrelate the transit signals from the astrophysical and instrumental noise, and ensure a higher degree of objectivity. [Waldmann (2012), Waldmann et al.(2013), Waldmann (2014)] suggested algorithms based on Independent Component Analysis (ICA) to extract information of an exoplanetary atmosphere from spectrophotometric datasets.

We adopt a similar approach to detrend the transit signal from photometric observations by using Point Spread Functions (PSFs) covering multiple pixels on the detector. We apply this technique to re-analyse some observations of primary transits recorded with Spitzer/IRAC. We present a series of tests to assess the robustness of the method and the error bars of the parameters estimated. Critically, by comparing the results obtained from different measurements, we discuss the level of repeatability of transit measurements in the IR, limited by the absolute photometric accuracy of the instrument and possible stellar activity effects.

2. The algorithm: pixel-ICA

The main novelty of the algorithms we use here is their ability to detrend the transit signal from a single photometric observation of just one primary transit. This is possible because, during an observation, there are several pixels detecting the same astrophysical signals at any time, but with different scaling factors, depending on their received flux, their quantum efficiency, and the instrument PSF. We performed an ICA decomposition over several pixel-lightcurves, i.e. the time series from individual pixels, in order to extract the transit signal and other independent components (stellar or instrumental in nature). Further details are reported in [Morello et al.(2014), Morello et al.(2015), Morello et al.(2015b)].

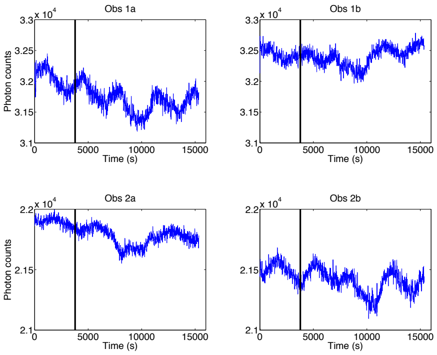

Figure 1: Raw integral light-curves of the four Spitzer/IRAC primary transit observations of GJ436b at 3.6 and 4.5 μm. Data points on the left of black vertical lines have been discarded for the analysis, on a statistical basis. Note that the transit depth is comparable with the amplitude of systematics.

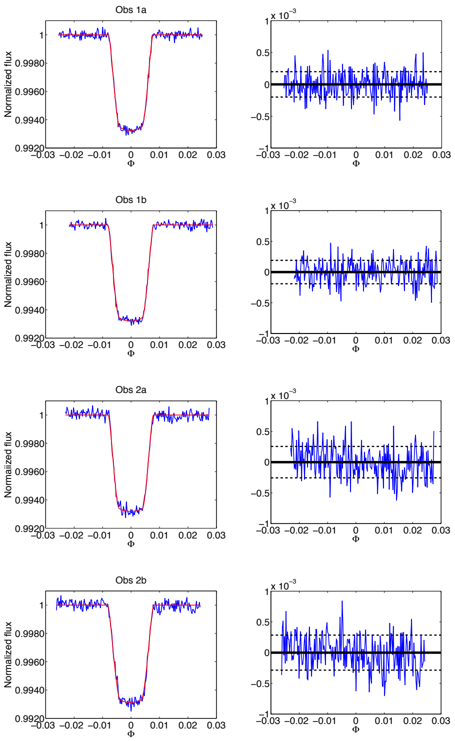

Figure 2: Left panels: (blue) detrended light-curves for the four observations with (red) best transit models overplotted, binned over 7 points; best transit models are calculated with p, a_0, and i as free parameters, and Phoenix quadratic limb darkening coefficients [Morello et al.(2015)]. Right panels: Residuals between detrended light-curves and best transit models; black horizontal dashed lines indicate the standard deviations of residuals.

3. Summary and Conclusions

We have introduced a blind signal-source separation method, based on ICA, to analyse photometric data of transiting exoplanets, with a high degree of objectivity; a novel aspect is the use of pixel-lightcurves, rather than multiple observations.

We have applied the method to reanalyse some Spitzer/IRAC datasets, which previous analyses found to give discrepant results, and obtained consistent parameters from these observations. We suggest the large scatter of results in the literature arises from the use of parametric methods to detrend the signals, neglecting the relevant uncertainties, and correlations.

We investigated the limits of our method on simulated observations.

We are applying this method to obtain robust and uniform results for a list of planets.

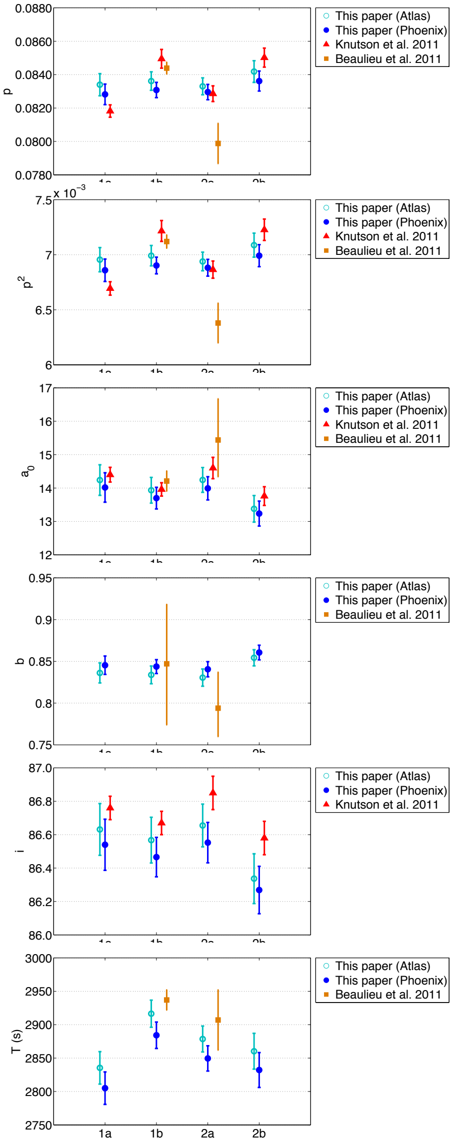

Figure 3: From top to bottom: Comparisons of the parameters p, a_0, and i (left side), p^2, b, and T (right side), obtained in this paper [Morello et al.(2015)] with Atlas stellar model (cyan, empty circles), Phoenix stellar model (blue, full circles), in [Knutson et al.(2011)] (red triangles), and in [Beaulieu et al.(2011)] (yellow squares).

Acknowledgements

G. Morello is funded by UCL Perren/Impact scholarship (CJ4M/CJ0T).

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