Exoplanet Characterisation Observatory (EChO)

Assessment Phase Payload Study

Decorrelating the planetary signal from instrumental and astrophysical noise

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Parametric and non-parametric approaches

The field of exoplanetary spectroscopy is as rapidly advancing as it is new. The aim to characterise smaller and smaller planets or reaching their atmospheric signal is equally a quest for higher and higher precision measurements, which are often limited by the systematic noise associated with the instrument with which the data are observed. This is particularly true for general, non-dedicated observatories. In the past, parametric models have extensively been used by most teams in the field of exoplanet spectroscopy/differential band photometry to remove instrument systematics (e.g. Agol et al. 2010; Beaulieu et al. 2008, 2010 , 2011; Burke et al. 2010; Charbonneau et al. 2005, 2008; Crouzet et al., 2012; Deming et al. 2007, 2013; Désert et al. 2011 ; Gibson et al. 2010; Grillmair et al. 2008; Knutson et al. 2007, 2008; Machalek et al. 2010; Pont et al. 2008; Sing et al. 2011a; Stevenson et al. 2010; Swain et al. 2008, 2009a,b; Tinetti et al., 2007, 2010). Parametric models approximate systematic noise via the use of auxiliary information of the instrument, the so called optical state vectors (OSVs). Such OSVs often include the X and Y-positional drifts of the star or the spectrum on the detector, the focus and the detector temperature changes, as well as positional angles of the telescope on the sky. By fitting a linear combination of OSVs to the data, the parametric approach derives its systematic noise model. We refer to this as the `linear, parametric' method. As shown in Fig. 1, in many cases precisions of a few parts in 10000 with respect to the stellar flux were reached.

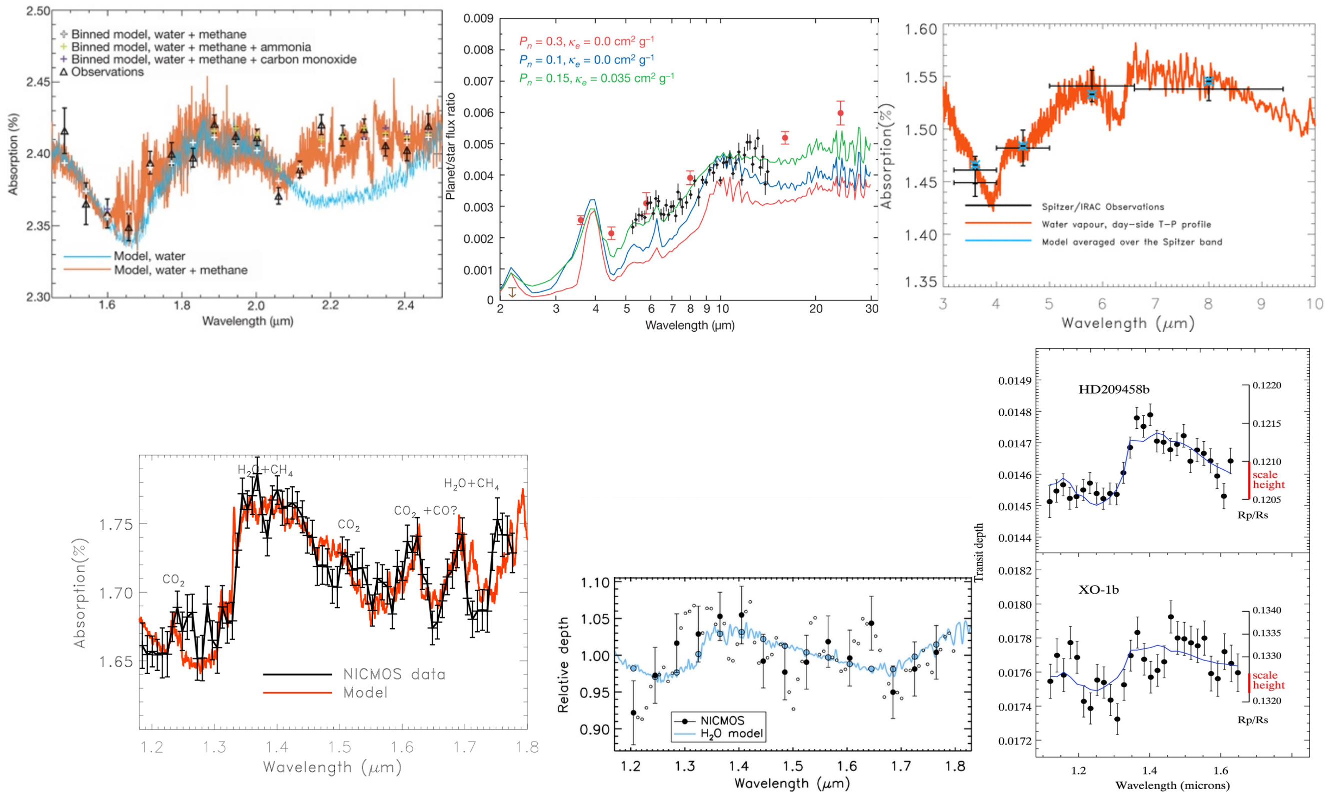


Fig. 1: Exoplanet spectra observed in the IR with Hubble and Spizter and analysed by different teams using parametric techniques. Top: Swain et al., 2008, Grillmair et al., 2008, Beaulieu et al., 2010. Bottom: Tinetti et al. 2010; Crouzet et al., 2012; Deming et al., 2013.

In the case of dedicated missions, such as Kepler (Borucki et al. 1996; Jenkins et al. 2010), the instrument response functions are well characterised in advance and conceived to reach the required 10^{-4} to10^{-5} photometric precision. EChO aims at reaching same level of photometric precision.

For general purpose instruments, not calibrated to reach this required precision, poorly sampled optical state vectors or a missing parameterization of the instrument often become critical issues. Even if the parameterisation is sufficient, it is often difficult to determine which combination of these OSVs may best capture the systematic effects of the instrument. This approach has caused some debates with current instrument regarding the use of different parametric choices to the removal of systematic errors.

Given the potential intricacies of a parametric approach, in the past years at UCL we have worked towards alternative methods to de-correlate the data from instrumental and stellar noise. The issue of poorly constrained parameter spaces is not new in astrophysics and has given rise to an increased interest in unsupervised (and supervised) machine learning algorithms. In particular so called blind-source separation algorithms. Cosmological and extragalactic observations, in particular, are often analysed through fully blind, non-parametric methods (e.g. Chapman et al. 2012; Stivoli et al. 2006; Wang et al. 2010). Unsupervised machine learning algorithms do not need to be trained prior to use and do not require auxiliary or prior information on the star, instrument or planet but only the observed data themselves. The machine learning approach will then (from observations) 'learn' the characteristics of an instrument and allows us to de-trend systematics from the astrophysical signal. This guarantees for the highest degree of objectivity when analyzing observed data. In Waldmann (2012, 2013b) and Waldmann et al. (2013), Independent Component Analysis (ICA; Hyvarinen 1999) has been adopted as an effective way to decorrelate the exoplanetary signal from the instrument in the case of Hubble-NICMOS and Spitzer/IRS data or to decorrelate the stellar activity from the exoplanet transit lighcurve, in Kepler data.

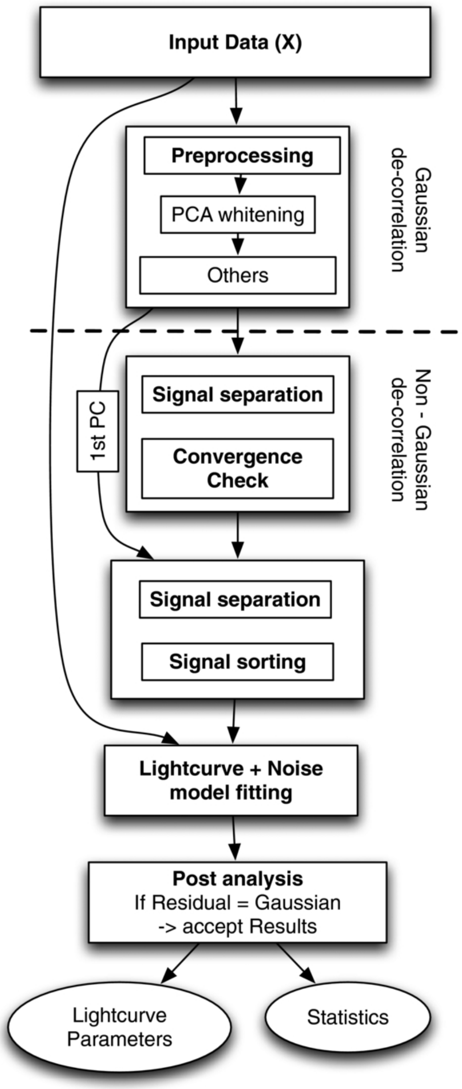
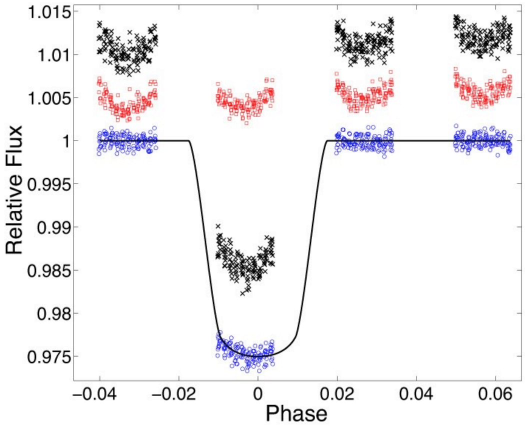


Fig. 2: Flowchart of the algorithmic de-trending of exoplanetary spectroscopic data using unsupervised machine learning (Waldmann 2012). First the Gaussian noise components are de-trended followed by a non-Gaussian noise decomposition. The data is then classified, and fitted with analytic models to produce the final exoplanetary spectrum.

We are now testing similar techniques to decorrelate Spitzer-IRAC data (G. Morello, MSc thesis, UCL-University of Palermo) and the new WFC3 camera onboard Hubble (R. Varley, MSc thesis at UCL) with very promising results. These results make us confident that we can apply these techniques to almost any instrument suitable to perform spectroscopy of exoplanet atmospheres, including EChO.



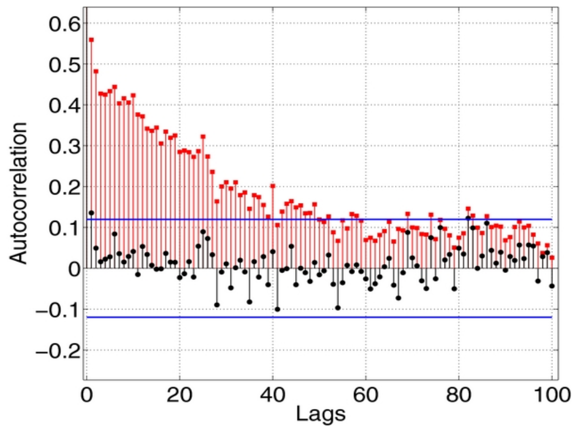


Fig. 3: Figures from Waldmann 2012. Left: Transit observation of HD189733b using Hubble/NICMOS. Black: raw observed data, note the strong (U-shaped trends). Red: ICA derived model of the instrument noise. Blue: corrected data with best-fit transit model overplotted (black line). Right: Autocorrelation plot of the raw data (red) and the corrected data (black). The blue lines show the 3 sigma limit for the corrected data not to have residual autocorrelative noise.

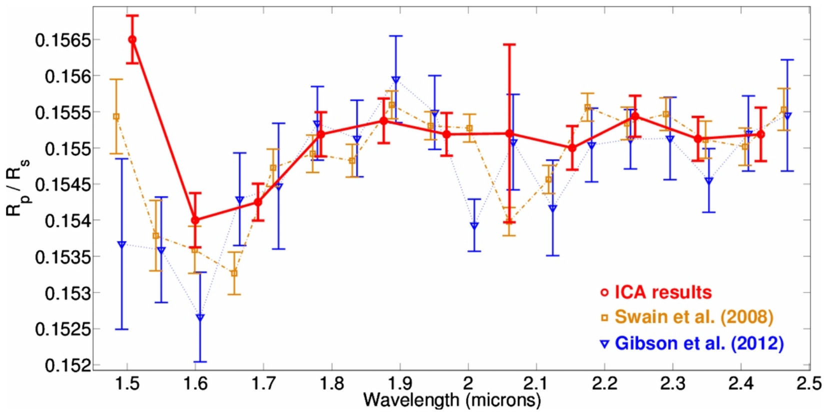


Fig. 4: Figure from Waldmann et al 2013: spectrum of HD189733b observed with NICMOS/Hubble. Comparison between parametric approach (Swain et al., 2008) and two different non parametric approaches (Gibson et al., 2012, Waldmann et al, 2013). The error-bars for non-parametric approaches are ~10–30% larger than those reported by S08. This difference is due to the higher amount of auxiliary information injected in the parametric approach. Ultimately, it is a trade-off between a higher degree of objectivity for the non-parametric methods and smaller errors for the parametric detrending. The fact that three very different analysis techniques yield comparable spectra is a strong indication of the stability of these results.

Astrophysical noise

Stellar noise is an important source of temporal instability in exoplanetary time series measurements. This is particularly true for M dwarf host stars as well as many non-main sequence stars. Correction mechanisms for fluctuations must and will be an integral part of the data analysis of EChO. The problem of stellar activity removal from time series data is a very active field of research (see TN Ribas, Micela). Whereas most instrumental effects can be measured or calibrated to some degree, stellar and general astrophysical noise does not usually grant us this luxury. Current research by UCL team is focusing on statistical methods to de-correlate astrophysical noise from the desired science signal (Waldmann, 2012; Danielski et al, submitted). Whilst the statistical fundamental of these methods are very different and often complementary, they all try to disentangle the astrophysical signal from various noise sources using the coherence of the exoplanetary transit/eclipse signature over time and/or frequencies of light. Fig. 5 left shows two examples of such a decorrelation. Given single time series on an active star with various modes of pulsation, obtained by the Kepler space telescope (blue dots), we could show that a randomly chosen pulsation mode of the star could be isolated and the remaining autocorrelative noise of the star suppressed, resulting in a strong reduction of the stellar noise component (red dots). Similar concepts apply to periodic exoplanetary lightcurves observed over multiple transits and/or wavelengths.

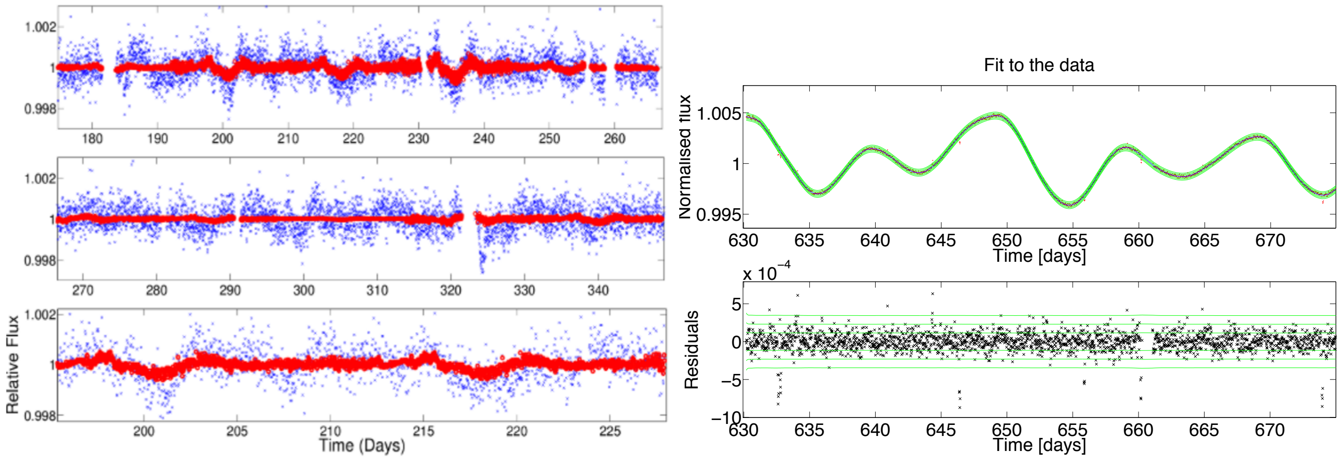


Fig. 5: Left: Kepler time series of an active M0 star (blue dots). Using Independent Component Analysis, the periodic pulsation filter at t=202, 218 and 235 was filtered from other correlated noise in the time series. The filtered signal is shown in red (Waldmann 2012). Right: Kepler time series of another active M0 star. Using a complementary method to ICA the stellar activity was successfully filtered out (Danielski et al., submitted).

Conclusions

Parametric and non-parametric approaches have been used in the past to decorrelate effectively the planetary signal from the instrumental systematics and astrophysical noise. The error-bars for non-parametric approaches can be sometimes larger than those reported by parametric approaches. This difference is due to the higher amount of auxiliary information injected in the parametric approach. Ultimately, it is a trade-off between a higher degree of objectivity for the non-parametric methods and smaller errors for the parametric detrending.

In the case of EChO we will make use of both methods to correct instrumental systematics and astrophysical noise. Very thorough tests and calibration of the instrument before launch (especially detector performances), will substantially help to constrain the auxiliary information of the instrument hence the decorrelation process.

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