Transmission spectroscopy using Gaussian Processes: Probing the haze of HD 189733b with HST/NICMOS + WFC3

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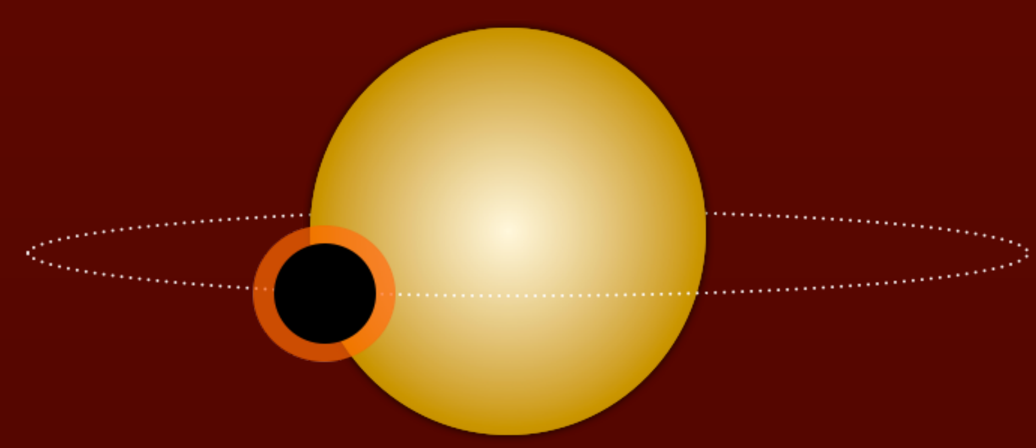

INTRODUCTION

Transmission spectroscopy is a technique used to measure the wavelength dependence of transiting planets' radii. Typically, transit light curves are modeled treating the planet as an opaque disk, with its size defined by the altitude at which the atmosphere becomes opaque to starlight (e.g. Seager & Sasselov 2000; Brown 2001). However, the optical depth in an atmosphere is wavelength dependent, being sensitive to atomic and molecular absorption. Thus, transmission spectroscopy is a measurement of the planet-to-star radius ratio (ρ) as a function of wavelength, and is a direct probe of the composition of a planet's atmosphere.

As transmission spectroscopy requires exquisite precision (~10^{-4} in transit depth), HST and Spitzer have provided the most detailed observations to date. Unfortunately light curves are always affected by instrumental systematics larger than the signal we are trying to measure, therefore their treatment is vital to extracting robust transmission spectra. Here, we summarise results from two papers: 1) A Gaussian process (GP) framework to model instrumental systematics and extract robust transmission spectra, applied to NICMOS transmission spectroscopy of HD 189733b (Gibson et al. 2011); 2) New observations of HD 189733b using HST/WFC3, also modeled using GPs (Gibson et al. 2012, submitted).

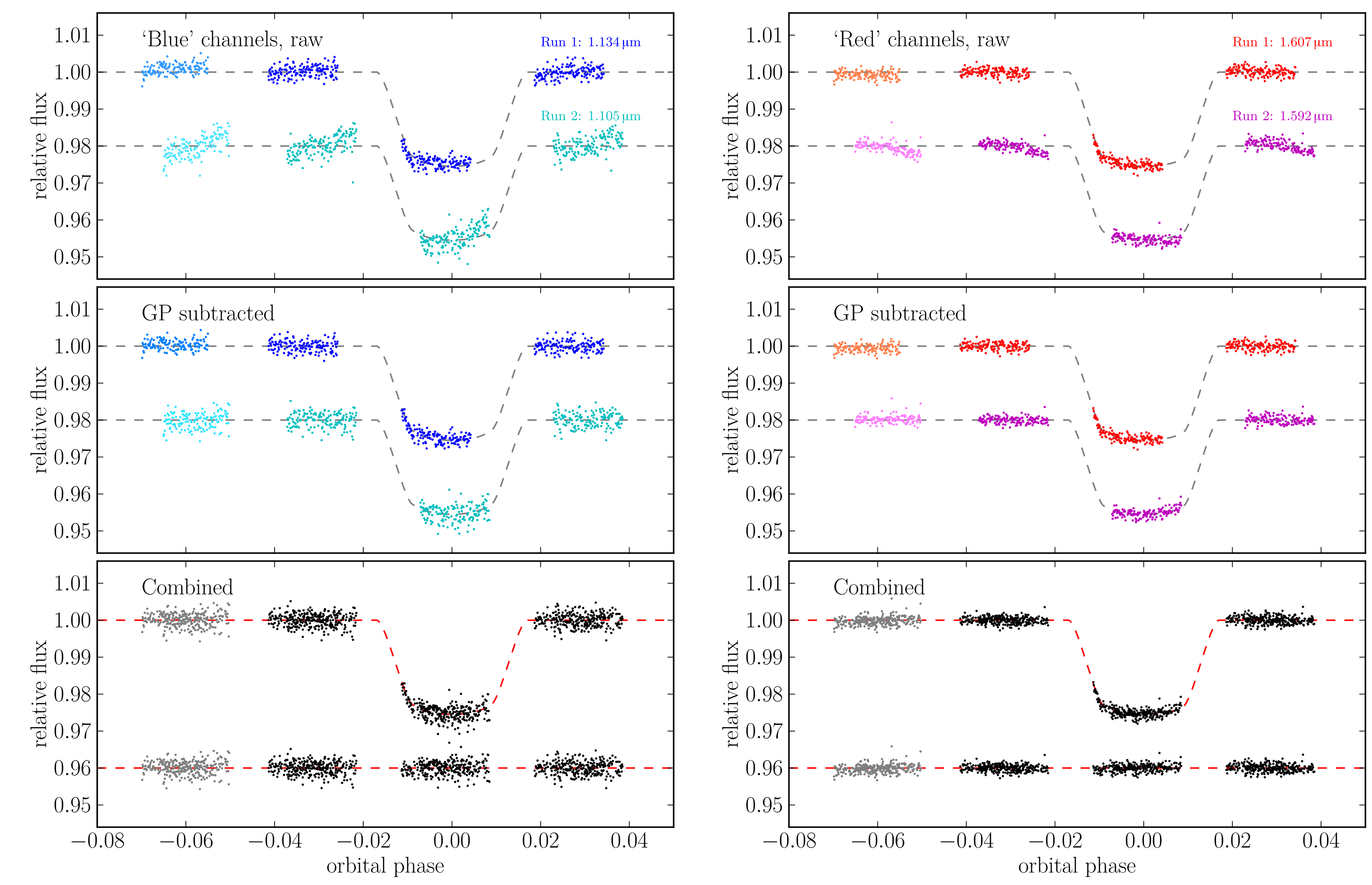

Fig. 1: WFC3 Dataset

The WFC3 dataset, consisting of two visits with HST. Due to saturation of the central region of the spectrum, only 'blue' and 'red' channels were extracted at ~1.1 and ~1.6μm, shown on the left and right plots, respectively. Transits were fitted using our GP model with a transit mean function and squared exponential kernel function. The inputs to the kernel were the orbital phase and spectral width.

The top panels show the raw light curves, i.e. before any correction for systematics. The middle panel shows the light curves after subtraction of the GP model, and the bottom panel shows both light curves combined. The GP model and the transit light curves are fitted simultaneously, and the planet-to-star radius radio is found after marginalising over all other variable (hyper-)parameters.

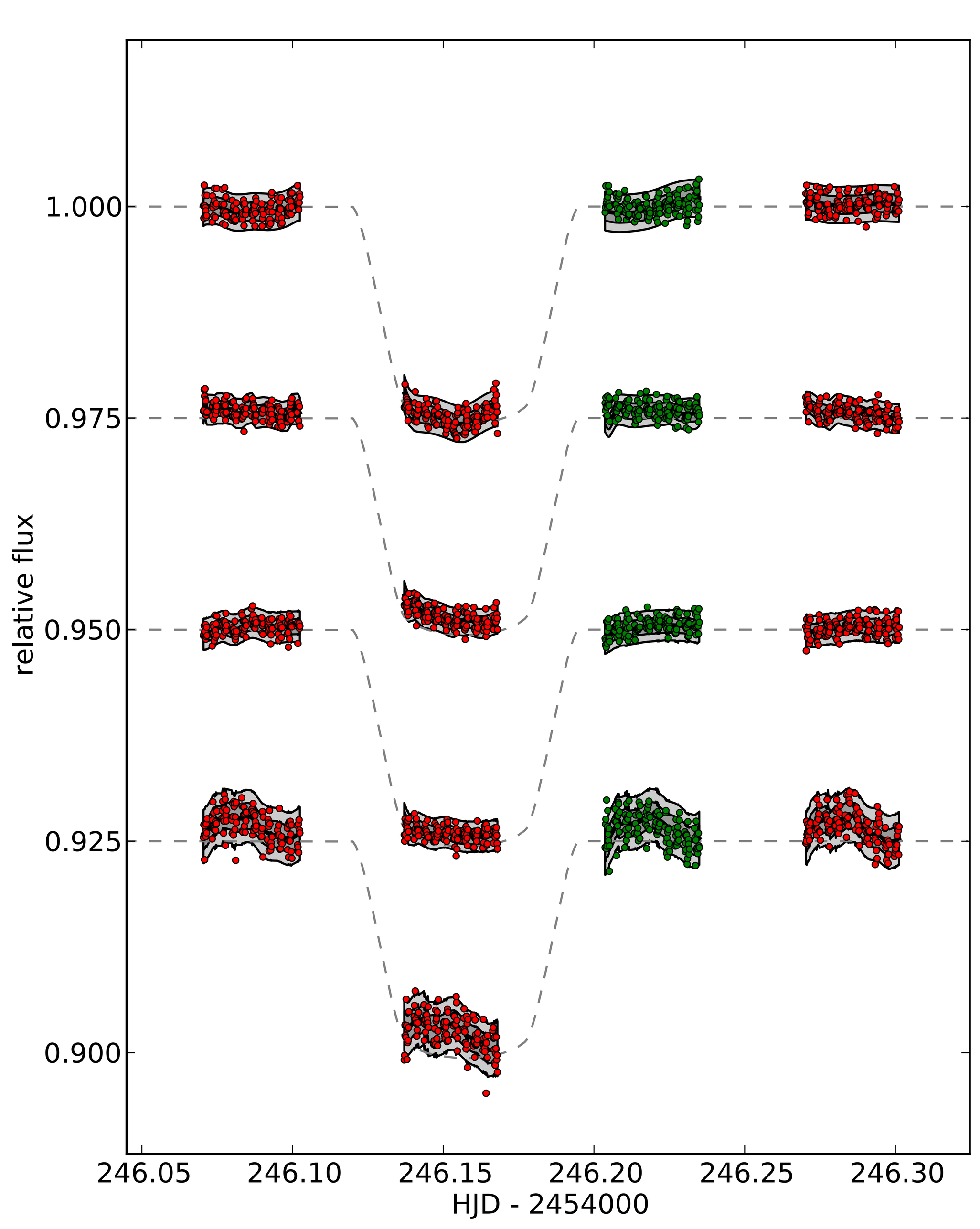

Fig. 2: NICMOS Dataset

Examples of NICMOS transit light curves of HD 189733. This dataset was originally analysed by Swain et al. (2008). Our reduction in total consists of 18 light curves from ~1.4 to 2.5μm. Each light curve was fitted with a GP with a transit mean function and a squared exponential kernel function with 6 auxiliary inputs, including the X and Y position of the spectrum, the width of the spectrum, the temperature of the detector, the angle the spectral trace makes with the X axis, and the orbital phase of HST.

In this example, the red points indicate points used to 'train' the GP, and the green points data that we make predictions for. The shaded grey regions represent the 1 and 2σ predictive distributions of the GP, showing our model does a very good job in predicting the instrumental response. All data points are used in practice to fit the model, and the parameters of the transit function and hyperparameters of the kernel are marginalised over when determining the planet-to-star radius ratio of HD 189733.

GAUSSIAN PROCESSES FOR TRANSMISSION SPECTROSCOPY

The 'standard' method to model instrumental systematics is to construct a parametric model as a function of auxiliary inputs (typically additional measurements made from the data, such as the position of the spectra, temperature, etc). Naturally the choice of systematics model has a large impact on the transmission spectrum, and can lead to spurious results; GPs offer an alternative to this.

GPs are an intrinsically Bayesian method that allow the systematics to be modeled in a non-parametric way, simultaneously with a transit (mean) function. Using a GP we can place a prior distribution over the function space that represents the systematics model, and therefore infer its form from the data rather than specify it *a priori*. We marginalise over all the parameters of the GP (hyperparameters), effectively marginalising out our ignorance of the form of the systematics model, leading to robust transit parameters. Figs 1 and 2 show applications of our GP model to WFC3 and NICMOS transmission spectroscopy. For more details see Gibson et al. (2011).

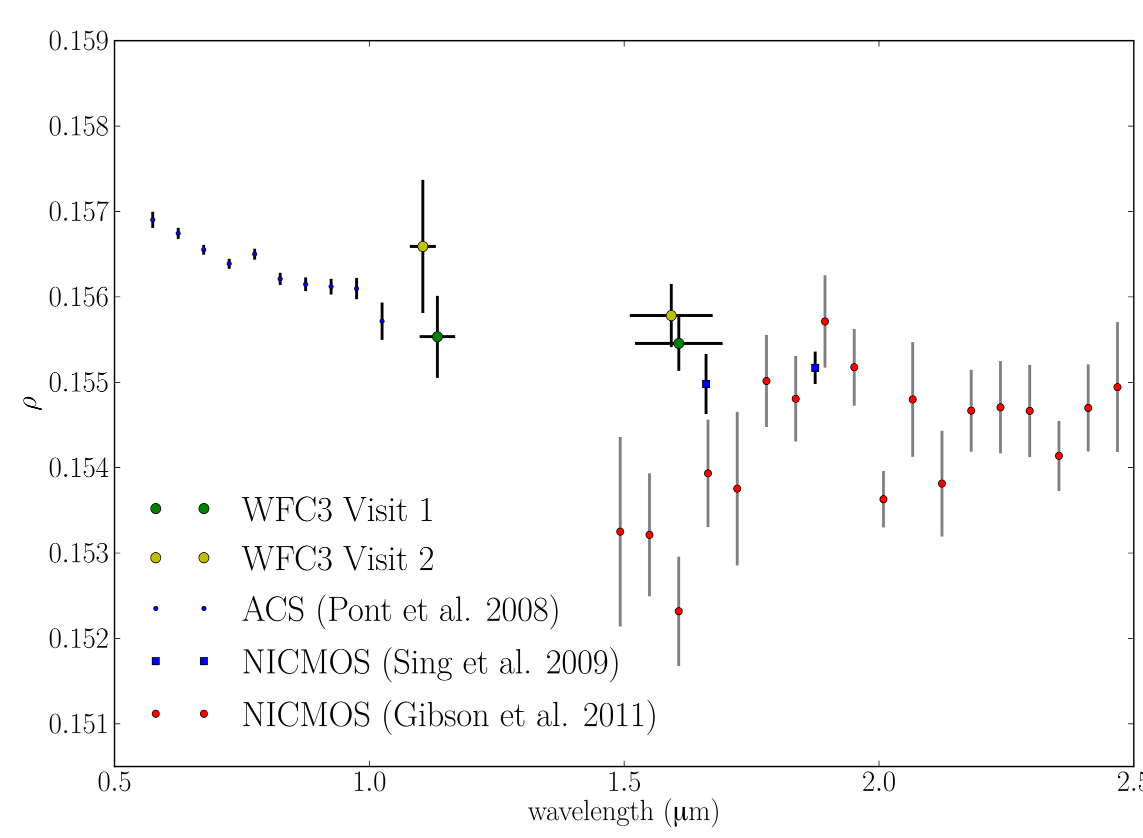

Fig. 3: Transmission spectrum of HD 189733

Transmission spectrum of HD 189733b showing the NICMOS and WFC3 data, alongside the ACS data of Pont et al. 2008, and NICMOS photometry of Sing et al. 2009. The data have been corrected for unocculted spots. All data are consistent with an extrapolation of the optical haze, except a feature in the NICMOS spectroscopy at ~1.6μm, likely of instrumental origin (Gibson et al. 2011). These data suggest the haze dominates the transmission spectrum out to NIR wavelengths, but more observations covering the ~1.0-1.4μm region are required to conclusively resolve the issue.

HD 189733 TRANSMISSION SPECTRUM

Our GP model was applied to NICMOS transmission spectroscopy and the new WFC3 data, shown in Figures 1 and 2. Fig 3 shows the resulting transmission spectrum, including the ACS data from Pont et al. (2008) and the NICMOS photometry of Sing et al. (2009). All data have been corrected for unocculted spots (see for example poster by T. Evans). The WFC3 data and the NICMOS transmission spectroscopy are consistent with an extrapolation of the optical haze, except for a feature at ~1.6μm in the NICMOS data. Gibson et al. 2011 note this is likely of instrumental origin, but given the difficulty in performing spot corrections it is difficult to rule it out from the WFC3 data alone. More detailed observations are required to confirm that the haze extends to IR wavelengths, or if molecular features start to dominate the transmission spectrum at these wavelengths.

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