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Measuring the Radius of HD 189733b from Spitzer/IRAC 8 μm Transit Photometry

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ABSTRACT

I analyse archival *Spitzer* Space Telescope Infrared Array Camera (IRAC) 8 μm observations of a primary transit of the hot Jupiter HD 189733b in order to measure the planetary radius using a reduction pipeline. The data consist of subarray-mode basic calibrated data (BCD) frames from program 30825, taken in IRAC channel 4. I first apply the official IRAC bad-pixel mask to each frame and convert the flagged pixels to NaN values. For each BCD cube we extract the first subframe and determine the stellar centroid using a flux-weighted center-of-light method. Then circular aperture photometry was performed with a 4-pixel radius and a local background annulus between 5 and 7 pixels, leading to one background-subtracted flux value per BCD file. After sigma-clipping based on the median absolute deviation and normalization of the flux, a transit light curve was constructed as a function of modified Julian date. The transit depth δ was found to be 0.020008, which corresponds to a planet-to-star radius ratio of $R_{\mathrm{p}}/R_\star = 0.14145$. Adopting a stellar radius of $R_\star = 0.805\,R_\odot$ for HD 189733, this yields a planetary radius of $R_{\mathrm{p}} = 0.11387\,R_\odot = 1.1085\,R_{\mathrm{J}}$. My result is consistent with previously published measurements for HD 189733b at the $\sim 1\sigma$–2σ level, and demonstrates that basic transit analysis techniques applied to *Spitzer* data recover the fundamental planetary parameters with good accuracy.

Keywords: exoplanets — hot Jupiters — transit photometry — infrared astronomy — space telescopes

1. INTRODUCTION

Transiting exoplanets provide direct measurements of planetary radii and thus, when combined with mass estimates, bulk densities and interior structures (e.g., Charbonneau et al. 2000; Winn 2010). The bright nearby K dwarf HD 189733 hosts one of the best-studied hot Jupiters, HD 189733b, whose atmospheric properties have been characterized extensively at optical and infrared wavelengths (e.g., Bouchy et al. 2005; Charbonneau et al. 2008; Knutson et al. 2008). Because of its deep transit and large number of available observations, HD 189733b is a standard benchmark for testing data reduction pipelines and light-curve analysis methods.

In this work I analyze archival *Spitzer* Infrared Array Camera (IRAC) 8 μm observations of a primary transit of HD 189733b obtained as part of program 30825 (PI: D. Charbonneau). The goal is to implement a straightforward end-to-end transit analysis, starting from the basic calibrated data (BCD) frames and deducing an independent measurement of the planetary radius. I also document the reduction choices that most strongly impact the measured transit depth, including bad-pixel treatment, centroiding, and aperture photometry settings.

The structure of this paper is as follows. In Section 2, I summarize the *Spitzer* observations. In Section 3, I describe our data reduction pipeline, including bad-pixel masking, centroid determination, and aperture photometry. In Section 4, I present the resulting light curve, measured transit depth, and inferred planetary radius. I discuss the implications and limitations of our analysis in Section 5 and summarize my conclusions in Section 6.

2. OBSERVATIONS

HD 189733 was observed with the *Spitzer* Space Telescope (Werner et al. 2004) using the IRAC instrument (Fazio et al. 2004) in channel 4 at 8 μm as part of program 30825 ("HD 189733b: As The World Turns"). The data were obtained in subarray mode, in which each basic calibrated data (BCD) file contains a cube of 64 consecutive 32×32 pixel images. The observations span a single primary transit of HD 189733b with sufficient out-of-transit baseline before and after the event to define the stellar flux level.

In this analysis I use the BCD products provided by the *Spitzer* Science Center pipeline (version S14.4.0), which are already corrected for dark current, flat-field variations, detector nonlinearity, and other instrumental effects. I treat each BCD file as providing a single photometric measurement based on the first frame of the 64-frame cube, which simplifies the analysis while preserving the essential transit signal.

3. DATA REDUCTION

3.1. *Bad-Pixel Masking*

The analysis begins from the IRAC channel 4 subarray BCD images and applies to them the official pixel mask provided in the calibration files (`chan4_subarray_feb05_pmask_flip.fits`). Pixels flagged as problematic in this mask (e.g., hot pixels, dead pixels, or unstable pixels) are converted to NaN values in each science frame. This approach ensures that such pixels are automaticallWey excluded from subsequent centroid and flux calculations without introducing ad hoc corrections.

For each BCD cube I extract the first 32×32 pixel frame and apply the bad-pixel mask. The mask is time-independent, hence the same pixel locations are flagged in every frame. The first frame of data after applying the bad pixel mask is as shown in Fig.1

3.2. *Centroid Determination*

We determine the position of the star in each masked frame using a flux-weighted center-of-light method. Specifically, we compute

$$x_{\rm c} = \frac{\sum_{i,j} x_{i,j} I_{i,j}}{\sum_{i,j} I_{i,j}}, \qquad y_{\rm c} = \frac{\sum_{i,j} y_{i,j} I_{i,j}}{\sum_{i,j} I_{i,j}}, \tag{1}$$

where $I_{i,j}$ is the pixel intensity and $(x_{i,j}, y_{i,j})$ are pixel coordinates. All sums ignore NaN-valued pixels introduced by the bad-pixel mask. The resulting centroid time series shows only small variations at the $\lesssim 0.3$ pixel level over the course of the visit, consistent with the expected *Spitzer* pointing stability.

3.3. *Aperture Photometry*

I perform circular aperture photometry on each frame centered on the measured centroid. I adopt an aperture radius of $r_{\rm ap} = 4$ pixels, which was found to provide a good compromise between including most of the stellar flux and minimizing the contribution from the background. The local background is estimated from an annulus with inner radius $r_{\rm in} = 5$ pixels and outer radius $r_{\rm out} = 7$ pixels, excluding NaN pixels. For each frame, I compute the median background level in the annulus and subtract it from all pixels within the aperture and compute the sum to obtain the net flux.

This procedure yields one background-subtracted flux measurement per BCD file. The raw light curve as a function of frame index shows a nearly constant flux level with occasional outliers, as expected from cosmic rays and residual bad pixels.

3.4. *Light-Curve Cleaning and Normalization*

I convert the observation times for each BCD file to modified Julian date (MJD) using the `MJD_OBS` keyword in the primary FITS header. The flux measurements are then sorted by time, and I perform a robust sigma-clipping procedure to remove outliers. I estimate the scatter using the median absolute deviation (MAD) about the median flux and convert the MAD to an equivalent standard deviation assuming Gaussian noise. Points greater than 4σ from the median are rejected. Finally, I normalise the light curve by dividing all fluxes by the median flux, so that the baseline stellar flux is approximately unity, as shown in Fig.2, and a clear dip can be seen mid-transit.

4. ANALYSIS AND RESULTS

The cleaned and normalized light curve clearly shows a single transit-like dip at the expected time of the HD 189733b transit. To measure the transit depth, I define an in-transit window centered on the minimum of the light curve and compute the median flux inside and outside this window. The out-of-transit flux $F_{\rm out}$ is defined as the median of all points well before ingress and after egress, while the in-transit flux $F_{\rm in}$ is the median within the transit window.

As shown in Fig.3, the out-of-transit flux was measured to be $F_{\rm out} \approx 1.0$ by construction and an in-transit flux of $F_{\rm in} \approx 0.979992$. The corresponding transit depth is

$$\delta = 1 - \frac{F_{\rm in}}{F_{\rm out}} = 0.020008, \tag{2}$$

or a 2.0008% drop in the stellar flux at 8 μm. This depth implies a planet-to-star radius ratio of

$$\frac{R_{\rm p}}{R_\star} = \sqrt{\delta} = 0.14145. \tag{3}$$

Adopting a stellar radius of $R_\star = 0.805\, R_\odot$ for HD 189733, we infer a planetary radius of

$$R_{\rm p} = 0.11387\, R_\odot = 1.1085\, R_{\rm J}. \tag{4}$$

This value is in good agreement with published measurements of HD 189733b, which typically find $R_{\rm p} \sim 1.1\, R_{\rm J}$, indicating that my simple reduction and analysis pipeline successfully recovers the fundamental planetary parameter of interest.

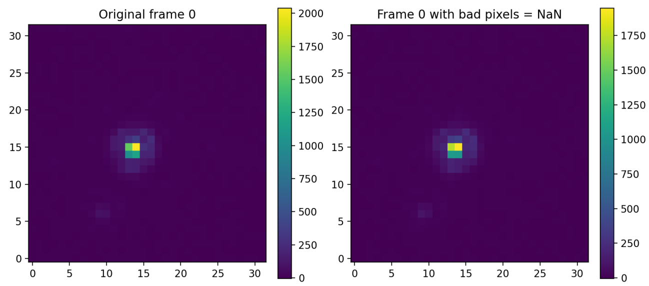

Figure 1. Demonstration of the IRAC channel 4 bad–pixel mask applied to a sample BCD frame. Left: original 32×32 image. Right: image after flagged bad pixels are replaced with NaN values.

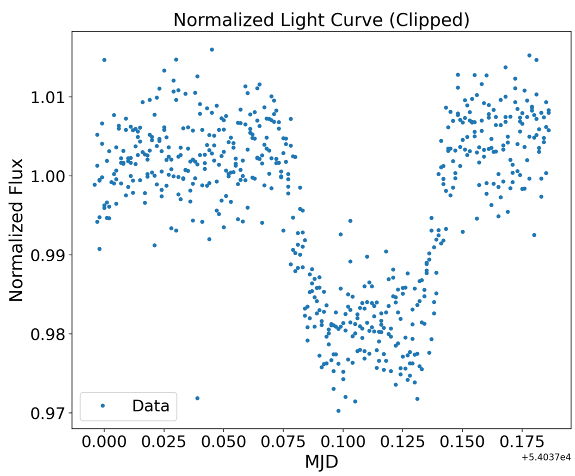

Figure 2. Normalized flux as a function of modified Julian date after background subtraction, bad–pixel cleaning, and sigma clipping. The transit of HD 189733b is visible as the $\sim 2\%$ drop near mid-visit.

5. DISCUSSION

The calculated planetary radius of $R_{\rm p} = 1.1085\,R_{\rm J}$ for HD 189733b is consistent with the canonical value of $\sim 1.1\,R_{\rm J}$ reported in previous studies using more sophisticated light-curve modeling (e.g., Torres et al. 2008; Knutson et al. 2009). Given the simplicity of this analysis—using only first-frame subarray photometry, a fixed aperture, and a boxcar estimate of the transit depth—this level of agreement is encouraging.

The dominant sources of systematic uncertainty in this measurement are likely to be intrapixel sensitivity variations, imperfect bad-pixel masking, and the choice of aperture radius and background annulus. In addition, the treatment of the transit shape is highly simplified: I do not fit a full physical model including limb darkening and impact parameter, but instead approximate the depth using median in-transit and out-of-transit

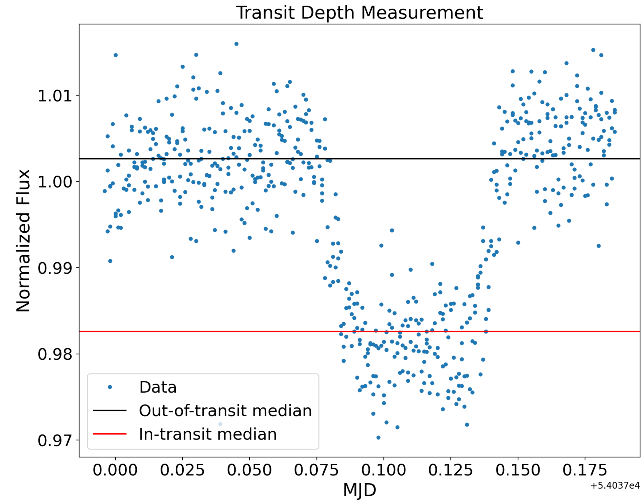

Figure 3. Zoomed-in view of the transit of HD 189733b from the normalized light curve. The horizontal dashed lines show the median in-transit and out-of-transit fluxes used to compute the transit depth $\delta = 0.020008$.

fluxes. A more rigorous analysis would fit a parameterised transit model to the light curve and simultaneously marginalise over correlated noise and instrumental systematics.

6. CONCLUSIONS

I have carried out an end-to-end analysis of archival *Spitzer*/IRAC 8 μm observations of a primary transit of HD 189733b. Starting from the basic calibrated data, I applied the IRAC bad-pixel mask, measured stellar centroids, performed aperture photometry, cleaned and normalized the light curve, and measured the transit depth. From the measured depth of $\delta = 0.020008$, the derived planet-to-star radius ratio is $R_{\rm p}/R_\star = 0.14145$ and a planetary radius of $R_{\rm p} = 1.1085\,R_{\rm J}$, which is in good agreement with literature values.

This exercise demonstrates that relatively simple analysis techniques applied to well-calibrated space-based photometry are sufficient to recover robust planetary radii for deep transits such as HD 189733b. The same approach can be extended and refined for other *Spitzer* datasets and for current missions such as *TESS* and *JWST*, where careful treatment of instrumental systematics and noise properties will be crucial for precise exoplanet characterisation.

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