Mon. Not. R. Astron. Soc. **000**, 1–**??** (2010) Printed 2 December 2010 (MN LaTeX style file v2.2)

Differential Photometry of WASP-5: A study of the light curve obtention methods

Néstor Espinoza[1⋆]
[1]*Departamento de Astronomía y Astrofísica, Facultad de Física, Pontificia Universidad Católica de Chile*

Received 2010 November 3

ABSTRACT
Using 178 exposures of 1 minute each at the Observatorio UC in Santiago, Chile, we present a study of the transiting exoplanet WASP-5b using WASP-5 star's lightcurve. After performing standard calibration on our frames, we performed a Laplacian Cosmic Ray Identification to substract cosmic rays from our images. Then, using three different algorithms (the TEPs group routines†, DPHOT (Broeg et. al, 2005) and a sigma-clipping algorithm) we computed the differential lightcurve of WASP-5 star. We then fit model light curves for the latter two methods using a quadratic limb darkening law and compare the planet-to-star radii using previously obtained results for the WASP-5b planet. We find an overall deviation of about a $\sim 21\%$ and atribute this to systematic errors and red noise present on our measurements. We also find signs of a probable variability of a star in our field. A discussion of the photometry performed with the different methods is made along with a discusion of re-derivations of previous known properties of the WASP-5b extrasolar planet.

Key words: extrasolar planets – methods: transits.

1 INTRODUCTION

Exoplanets is a widely (now) known field of important research in astrophysics. Since the first detection of a transiting exoplanet (Charbonneau et. al, 2000), the transit method has been a very popular one among professional and amateur astronomers due to it's apparent simplicity of just needing (good) photometry to be applied.

Although the transit method for extrasolar planet detection is relatively new, the study of the variations on the brightness of astronomical objects with time is a much older and well known field of research in binary or variable stars, for example. Despite of this, it was not until the arrival of the CCDs that it was possible to perform it with high precision (Howell & Jacoby, 1986). The traditional method for the study of a variable source is known as differential photometry.

1.1 Differential photometry

If we want to measure the variability of a star with a telescope, we have to account for atmospheric variations on our signal. One way of doing this is to compare our target star with others present in the field. If we assume that the star S is the variable one and we take a star C as a comparison star, assuming that it isn't variable, then to first approximation the flux of these stars is given by:

$$\begin{aligned} F_S^o &= K(t)F_S^r \\ F_C^o &= K(t)F_C^r \end{aligned}$$

Here F^o denotes the observed flux and F^r denotes the real flux of the source (we have omited the obvious dependance of K and F with wavelength). $K(t)$ is a variable factor that can either decrease or increase the flux of our targets. In terms of magnitudes we can write:

$$\begin{aligned} m_S^o &= -2.5\log(K(t)F_S^r/F_0) \\ m_C^o &= -2.5\log(K(t)F_C^r/F_0) \end{aligned}$$

Where F_0 is the standard zeroth-magnitude flux for the chosen filter. Taking the difference of these magnitudes we get:

$$\Delta m = m_S^o - m_C^o = -2.5\log(\frac{F_S^r}{F_C^r}) = -2.5\log(F)$$

Here $F = F_S^r/F_C^r$ denotes the relative flux ratio of our source and comparison stars, and will be used troughout this work as a measure of the relative flux of our source i.e, we'll assume that if we observe variations of this difference in magnitude with time, we'll be observing the variation of the flux on our variable object S.

⋆ E-mail: nsespino@uc.cl

2 THE DATA

2.1 Image obtention

The images of our field were obtained at the Observatorio UC using the 40 cm MEADE telescope with the SBIG ST-L-1001 3 CCD Camera. We took 178 exposures of 1 minute each using the V filter with a relatively new proposed method of telescope defocusing (Southworth et. al, 2009) which helped to reduce the noise on our images by spreading the PSF into more pixels in our CCD and to avoid saturation of all of our bright stars in our field, which permitted us to do longer exposure times.

The observations where centered at the WASP-5 star (the coordinates of the center of our field where RA 23:45:45, DEC -41:16:29, epoch J2000), but a poor tracking problem of the telescope made variations on the center coordinates of our images. The time of the observation was calculated knowing the planet's period to be $P = 1.628430 \pm 0.000013$ days (Gillon et. al, 2009). An image of our field can be seen in Figure 1.

2.2 Data reduction

After bias, dark and flat correcting our images we used the PYTHON version of the Laplacian Cosmic Ray Identification algorithm designed by van Dokkum (van Dokkum, 2001) to eliminate cosmic rays and bad pixels present on our images. This was important because without the proper extraction of such bad pixels, the photometry would have been biased and lead to an overestimation of the flux of our stars.

The photometry was made to the brightest non-saturated stars of our field. The chosen stars can be seen in Figure 1, where we labelled each comparison star (C_n) and our target star (WASP5). In order to perform the photometry on our stars, we first aligned all our images using the `imal2` task from the TEPs group routines[1]. Then, we performed aperture photometry using two different methods: VPHOT (Deeg et. al, 2001) from the TEPs group routines and DAOPHOT's `phot` IRAF task. The first one was used only for a comparison between the different methods we use to obtain our light curves (see the Data analysis section) because VPHOT routine calculates automatized aperture radii using `apcalc` asuming a gaussian PSF for the stars. Because we defocused our telescope, our objects had no longer perfect gaussian PSF's so any asumption on that basis would lead to biased results. On the other hand, DAOPHOT's `phot` routine gave us the flexibility of chosing an aperture radius for our stars, along with an aperture radius to calculate the sky level. We choose an aperture radius of 8 pixels mainly because all stars, except for C_1 and C_2, where far from each other and an sky aperture anulus of 12 pixels.

[1] http://www.iac.es/project/tep/tephome.html

Label	Inst. Mag.	σ-Error
WASP5	12.64	0.25
C_1	12.34	0.13
C_2	13.22	0.13
C_3	12.40	0.10
C_4	14.38	0.12
C_5	13.95	0.07
C_6	12.25	0.28
C_7	12.82	0.41
C_8	12.61	0.23

Table 1. Information on our instrumental magnitudes. Note the difference between the σ-errors.

3 DATA ANALYSIS

3.1 The instrumental magnitudes

In order to select the brightest stars for comparison, we computed the instrumental magnitudes of our stars. Table I shows our instrumental magnitudes and their corresponding $1-\sigma$ error. We note that the σ-errors **are not** signs of transit, but a measure of the scatter of the data troughout the exposures (which is a function of the color and magnitude of our stars). According to this results, our best candidates for comparison stars are C_1, C_2, C_3, C_4 and C_5.

3.2 Variability test for our stars

As proposed by Howell et. al (1988), we can compare the variances from the differential magnitudes in order to detect variable sources on our data. To do this, we first made an algorithm that calculated the square root of the variances (i.e. the standard deviation) between all of our stars (i.e., we made light curves with the differential magnitudes $\Delta m_{c_i - c_k}$ where $i \neq k$). We found that our best candidate to be a comparison star is C_1 and found that C_2, C_3 and C_6 had the lowest variances (0.009, 0.006 and 0.005 when compared to C_1), WASP5, C_4 and C_5 had similar ones ($\sim$ 0.02, 0.04 and 0.03 respectively when compared to C_1) and C_7 and C_8 had the highest ones ($\sim$ 0.4 and 0.23 when compared to C_1). According to this test, we are only left with 4 comparison stars: C_1, C_2, C_3 and C_6. To be highly conservative and according to the obtained σ-errors on these comparison star's magnitudes, we only considered C_1, C_2 and C_3 on the present work as our final comparison stars.

3.3 Obtention of the light curves

In order to get our differential magnitude light curves we performed three different methods. The first was using the VAPHOT (IRAF task) for the photometry and Vanaliz (IDL routine) to perform the analysis on the differential magnitude light curves (Deeg et al., 2009, hereafter the TEP Method). The second method we present was made using DAOPHOT for the photometry and DPHOT (Broeg et. al,

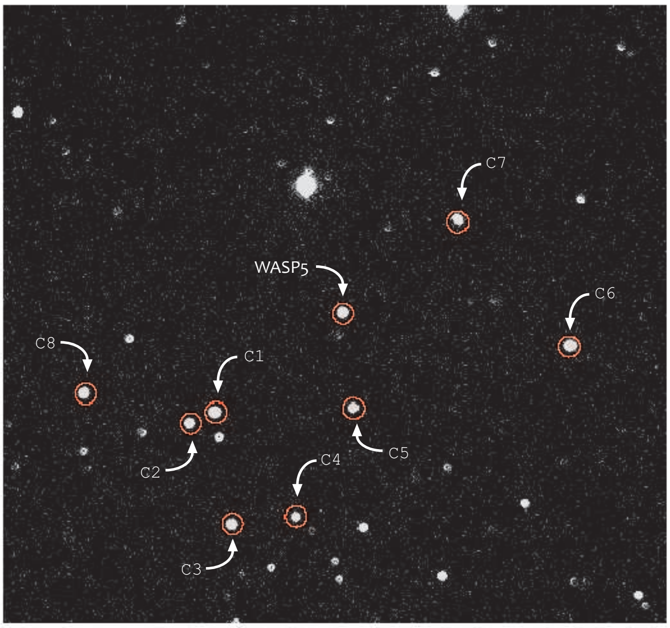

Figure 1. Image of our field. The stars used in the present work are labelled, where C denote the comparison stars we use in the present work. The anulus around each star has a 7 pixel radius. Note that in fact there are brighter stars in our field, but they where all saturated.

2005) for the differential magnitude light curves creation (hereafter the Broeg Method) and the third method was a sigma-clipping algorithm to be explained on the next subsections (hereafter the SC method).

In general our data showed a 1-σ error of about ~ 7 milimagnitudes, but a general much higher scatter on our differential magnitudes is present due to systematic errors not taken into account (see the Discussion section). Because we are trying to detect a planet around the WASP5 star (i.e. the in-transit flux will be at most $\sim 97\%$ of the off-transit flux), we define our transit data set (which is a subset of all of our data) as follows: we take the off-transit mean differential magnitude (taking all magnitudes before $t_{OT} = 2455479.65$ (HJD), as we inspected visually, sigma-clipping it), $\Delta\bar{m}_{OT}$, and define the subset:

$$T : [\Delta\bar{m}_{OT} - 6\sigma, \Delta\bar{m}_{OT} + 6\sigma - 2.5\log(0.97)]$$

Of our data set. We took 6σ on our limit because we want to account for those data points in the worst-case scenario. The set T then is our final transit data set.

3.3.1 Obtaining the light curves from the TEP Method

As mentioned earlier, the photometry of this method was made using VAPHOT, an IRAF task that does aperture photometry with the help of `apcalc` which calculates the optimum aperture radius for the photometry automatically. The VAPHOT task then performs the photometry on every image using the calculated aperture radii and gives those magnitudes as a function of time (HJD) for each image. Then, the output can be passed to the `vanaliz` IDL routine which analyses the data and creates a synthetic comparison star. Initially, the `vanaliz` routine uses all the stars we selected as comparison stars and weights them according to their variability, their magnitude and the fraction of light of the stars present on the synthetic comparison star. A result involving the three comparison stars used to calculate the synthetic star is shown in Figure 2 and the differential magnitudes computed using each comparison star separately are shown in Figure 3. We couldn't fit any curve to the data because the routine doesn't give any errors on the differential magnitudes.

Despite the fact we couldn't fit any curves, we did measure the off-transit and in-transit mean magnitudes to be $\Delta\bar{m}_{OT} = -0.163\pm0.008$ and $\Delta\bar{m}_{IT} = -0.121\pm0.026$ respectively. In terms of flux, this means that the in-transit flux is a $96.22\pm2.42\%$ of the off-transit flux, which gives us a planet-to-star radius ratio of approximately $\sim 0.194 \pm 0.0625$.

3.4 Obtaining the light curves from the Broeg Method

As mentioned, we used DAOPHOT's `phot` task to perform aperture photometry using an aperture radius for our objects of 8 pixels and an sky aperture anulus of 12 pixels. Then, the data was procesed by DPHOT using the three mentioned comparison stars (C_1, C_2 and C_3). Basically, DPHOT separates our target star from our comparison stars. For each comparison star all remaning comparison stars are used to compute this comparison star's differential

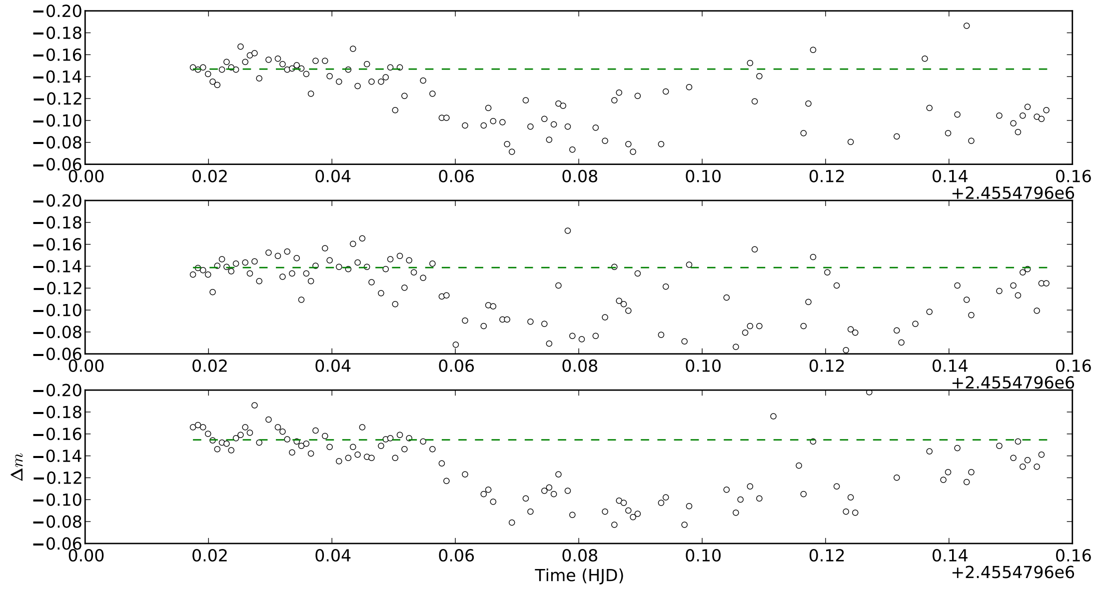

Figure 3. Differential magnitude light curves using C_1 (top), C_2 (middle) and C_3 (bottom) as comparison stars. The dashed line shows the mean off-transit magnitude in each case.

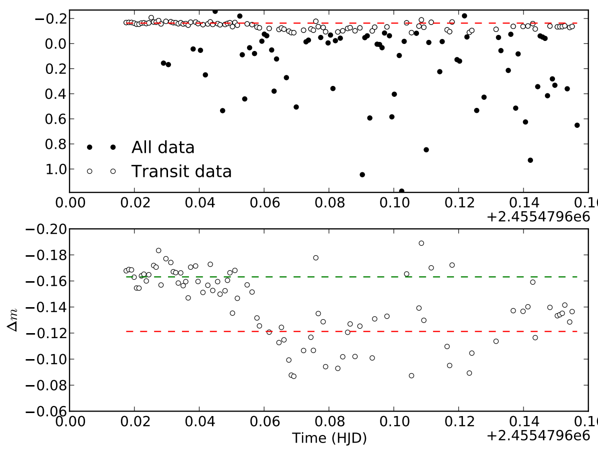

Figure 2. Differential magnitude light curve using C_1, C_2 and C_3 to form a synthetic comparison star using the TEP method. The top figure shows all data and the T transit subset on the same figure and the bottom figure shows only the transit data. In the bottom figure the upper dashed line shows the mean off-transit magnitude and the bottom one the mean in-transit magnitude.

magnitude. Then, the dispersion on this differential magnitude is used to weigh this star and this iterative process is made with every comparison star present on the set. Finally, the weights are used to compute the final synthetic star and this is used as the comparison star for our target star. Figure 4 shows the final differential magnitudes of WASP5 using C_1, C_2 and C_3 as comparison stars. We measured the off-transit and in-transit mean magnitude to be $\Delta\bar{m}_{OT} = 0.037 \pm 0.010$ and $\Delta\bar{m}_{IT} = 0.059 \pm 0.023$ respectively. In terms of flux, this means that the in-transit flux is a $97.99 \pm 2.33\%$ of the off-transit flux, which gives us a planet-to-star radius ratio of approximately $\sim 0.141 \pm 0.082$.

We used the `jktebop`[2] FORTRAN routine (Southworth, 2008) to fit a model light curve to our data. This routine is based on the EBOP code written originally for eclipsing binary stars by Paul B. Etzel (Popper & Etzel, 1981, Etzel, 1981). Because WASP-5 is a relatively cold star of 5880 ± 150 K (Anderson et al., 2008) we used a quadratc limb-darkening model for our star with $u_1 = 0.4$ (linear coefficient) and $u_2 = 0.3$ (non-linear coefficient) (Claret, 2000). For simplification, we also assumed spherical bodies, a circular orbit ($e = 0$), a $i = 90$ deg. inclination angle and a period $P = 1.6284$ days. The results of the fit are shown on Figure 5.

The output of the fit gives the planet-to-star ratio, the sum of the parametrised radii ($r_A + r_B$ where $r_A = R_A/a$ and $r_B = R_B/a$, R_i being the absolute radius of the object i and a the semi-mayor axis of the two-body orbit) and the time of minimum light. These results are shown on Table II.

3.5 Obtaining the light curves from the SC Method

Using DAOPHOT's `phot` task to perform aperture photometry (as explained in previous sub-sections), we obtained instrumental magnitudes for each of our stars. Then, for each magnitude of our comparison stars we performed a sigma-clipping algorithm, leaving only the magnitudes

[2] The source code can be found at John Southworth's personal website: http://www.astro.keele.ac.uk/∼jkt

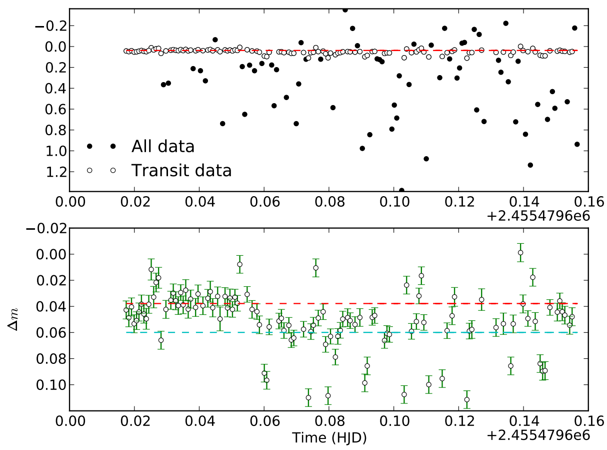

Figure 4. Differential magnitude light curve using C_1, C_2 and C_3 to form a synthetic comparison star using the Broeg Method. The top figure shows all data and the T transit subset on the same figure and the bottom figure shows only the transit data. In the bottom figure the upper dashed line shows the mean off-transit magnitude and the bottom one the mean in-transit magnitude.

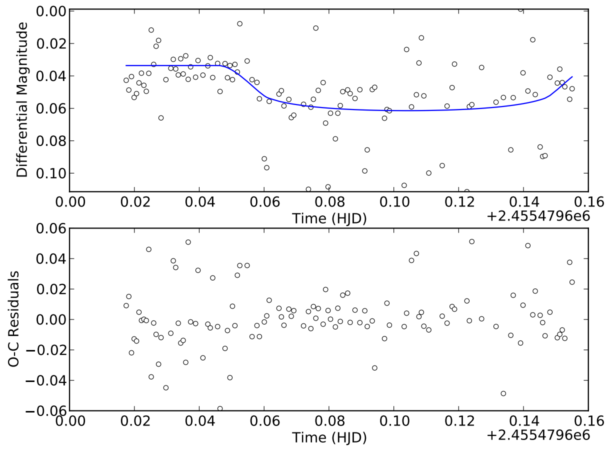

Figure 5. Best fit to our data using `jktebop` (error bars have been ommited for visualization) for the Broeg Method. The residuals of the O-C (observed minus computed) values are shown. The normalized (by number of data points) sum of the residuals is 149 mmag.

close to the mean value. The same method was applied to our target star because, as we saw, a change of flux of about 97% involves a deviation in magnitude of $\sim -2.51\log_{10}(0.97) = 0.03$ from it's mean value (i.e. it's off-transit value). After sigma-clipping our target star we got a standard deviation of 0.07 which clearly preserves the transit (if present). This removes partially all of the noisy data from our magnitudes. Then, we obtained the individual light curves for each of our comparison stars and finally selected the times at which we actually had data in the three light curves, because if in one light curve the magnitude of the comparison star was sigma-clipped it was

Property	Value	σ-Error
u_1	0.4	N/A (fixed)
u_2	0.3	N/A (fixed)
e	0	N/A (fixed)
i	90 deg	N/A (fixed)
P	1.6284	N/A (fixed)
k	0.143	0.002
$r_A + r_B$	0.221	0.004
t_{min}	2455479.7040	0.0009

Table 2. Output of the `jktebop` fit to our light curve using the Broeg Method. According to Southworth, the $1-\sigma$ errors given by the output file are too optimistic specially if the data has clear signs of red noise (see the Discussion section). This is made clear from the approximate calculation of the k value on our analysis.

Property	Value	σ-Error
u_1	0.4	N/A (fixed)
u_2	0.3	N/A (fixed)
e	0	N/A (fixed)
i	90 deg	N/A (fixed)
P	1.6284	N/A (fixed)
k	0.144	0.001
$r_A + r_B$	0.216	0.003
t_{min}	2455479.7032	0.0006

Table 3. Output of the `jktebop` fit to our light curve using the Sigma-Clipping Method. According to Southworth, the $1-\sigma$ errors given by the output file are too optimistic specially if the data has clear signs of red noise (see the Discussion section). This is made clear from the approximate calculation of the k value on our analysis.

probably because of a global factor (airmass, for example), and we think of that data as biased. Finally, from the remaining data that passed all these tests we obtained a final light curve taking the mean of our three light curves. This curve is shown on Figure 6.

We measured the off-transit and in-transit mean magnitude to be $\Delta\bar{m}_{OT} = -0.138 \pm 0.007$ and $\Delta\bar{m}_{IT} = -0.112 \pm 0.023$ respectively. In terms of flux, this means that the in-transit flux is a $97.62 \pm 2.16\%$ of the off-transit flux, which gives us a planet-to-star radius ratio of approximately $\sim 0.154 \pm 0.070$.

A fit was also made using the `jktebop` routine, where the assumptions are the same as for the Broeg Method. The results of the fit are shown on Figure 5 and Table III.

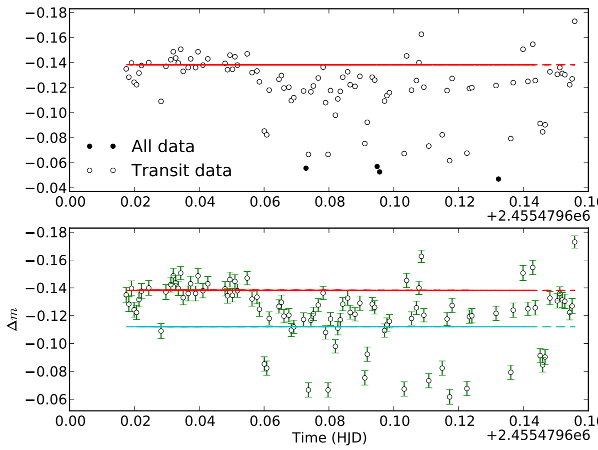

Figure 6. Differential magnitude light curve using C_1, C_2 and C_3 to form a synthetic comparison star using the Sigms-Clipping Method. The top figure shows all data and the T transit subset on the same figure and the bottom figure shows only the transit data. In the bottom figure the upper dashed line shows the mean off-transit magnitude and the bottom one the mean in-transit magnitude.

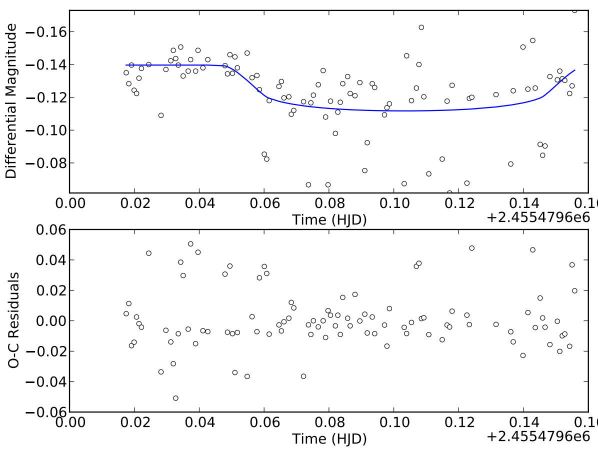

Figure 7. Best fit to our data using `jktebop` (error bars have been ommited for visualization) for the Sigma-Clipping method. The residuals of the O-C (observed minus computed) values are shown. The normalized (by number of data points) sum of the residuals is 120 mmag.

3.6 Possible variability detection on C_4

As shown on the "Variability test of our stars" section, C_4 and C_5 differential magnitudes had similar standard deviations to WASP5. This made us think that they actually varied with time and we double-checked it visually. We found no evidence in C_5 but we did on C_4. Figure 8 shows the differential magnitude curve obtained by the Broeg Method.

If the source varies by some physical reason, according to our calculations it is probably not a planet because of it's

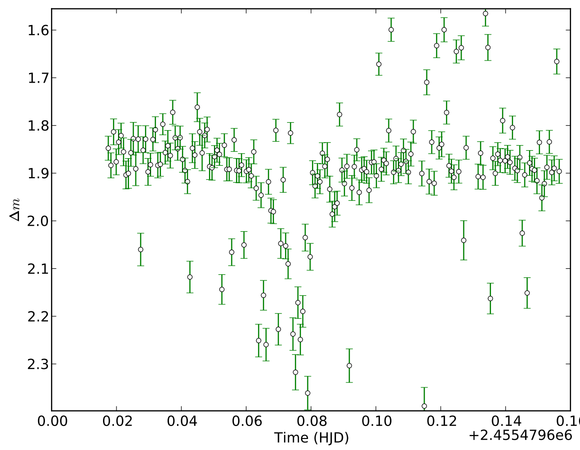

Figure 8. Differential light curve for C_4 star obtained using the Broeg Method.

off-transit and in-transit magnitude difference, measured to be approximately $\Delta m \sim 0.35$. In terms of flux, this means that the in-transit flux is a $\sim 72.5\%$ of the off-transit flux.

4 DISCUSSION

4.1 Obtention of the light curves

According to our analysis, the obtention of the light curves by the three different methods was different, although some similarity between the Broeg and the Sigma-Clipping Method's can be seen (120 mmag of normalized residual sum versus 149 mmag, respectively). We atribute this mainly to the way we did the photometry, DAOPHOT's `phot` task being the most reliable tool for an optimum photometry given it's flexibility. The problem with the TEP's `VAPHOT` routine was mainly the use of `apcalc` in the calculations of the optimum aperture radii for our stars because it assumes a perfect gaussian distribution which isn't the case for our data (because we performed the telescope defocusing technique).

Comparing our fitted results for the sum and ratio of the radii of our system with known values given by Southworth (2009) we can see a deviation of about a $\sim 21\%$ from previously derivated values (~ 0.11 for the k value in Southworth's work versus our ~ 0.14 value obtained in the present work). We atribute this deviation mainly to the strong red noise present on our data. As we could investigate from the literature, the error analysis of transit light curves is highly complex if one wants to account for as many factors as possible. These range from the well known photon noise and atmospheric variability to CCD sensitivity and proper flat-fielding (Hidas et al., 2005, Manfroid et al., 2001). Many of the works (if not all) on trasiting extrasolar planets cited in the present work use an algorithm to fix the red noise present on the data named `Sys-Rem` (Tamuz et al., 2005). Basically, the algorithm is motivated by the need to account for the usually unkown color (wavelength) variable present on the data, searching for a correlation between the airmass and the residuals of the stellar magnitude (i.e. the stellar magnitude after substrating the average magnitude of the individual star). Generalizing this concept to any effect appearing on the data, the Sys-Rem algorithm removes any linear appearing effect in a given set of lightcurves. As we could see from works done in sites with non-optimum conditions (Raetz et al., 2008) the use of this kind of algorithms are essential for obtaining decent light curves.

4.2 Possible variability of the C_4 comparison star

As we could inspect visually and statistically using a simple test, the detection of variability on the C_4 comparison star is a subject for further study. Stronger tests of stellar variability should be made to confirm this proposition. As mentioned in the Data analysis section, if the variability exists it is probably not due to a transiting planet given the large amount of flux covered by the (possible) transiting object.

5 CONCLUSION

According to our data, the transit of the WASP-5b planet was detected but the large noise contribution biased all possible results obtainable from it. Our measurements also lacked of after-transit magnitudes and this made it difficult for our light curves fits to converge properly. On the other hand, we believe that stronger data analysis is needed (using Sys-Rem, for example) to remove linear correlated noise on our measurements.

We also detected possible variability of the C_4 comparison star and propose further follow up of this star in order to confirm it. If true, it seems unlikely to be a transiting exoplanet given the high ammount of flux covered by the (possible) transiting object ($\sim 27.5\%$).

Finally, the detection of a transiting exoplanet from the Observatorio UC is clearly a motivation for further studies from small diameter telescopes: they are the proof that size really doesn't matter when you have the apropiate data analysis tools for your measurements.

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