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Photometry of Transients and Variable Sources at the Osservatorio Polifunzionale del Chianti (OPC)

L. Naponiello[a,b], D. Trisciani[b], L. Betti[a,b], A. Biagini[a,b], R. Stanga[b], M. Agostini[a,b], M. Focardi[b,c], and E. Pace[a,b]

[a]University of Florence - Department of Physics and Astronomy, Largo E. Fermi 2, 50125 Firenze - Italy
[b]Osservatorio Polifunzionale del Chianti, 43°31′24″ N - 11°14′44″ E, Barberino Val dElsa (Firenze) - Italy
[c]INAF-OAA, Arcetri Astrophysical Observatory, Largo E. Fermi 5, 50125 Firenze - Italy

ABSTRACT

The *Osservatorio Polifunzionale del Chianti* is a new astronomical site located in the neighbourhoods of San Donato in Poggio (Firenze), on top of one of the highest hills of the Chianti area, among the darkest places in Tuscany, and it is managed by the University of Florence. The name takes origin from the different observatories that are hosted in the building. Beside the Astronomical Observatory, Geo-seismic, Meteorological and Environmental Observatories fully operate in a fruitful synergic collaboration among themselves.

Presently, the main research activity at OPC concerns the observation and follow-up of transiting exoplanets while the team is involved in national and international collaborations, like TESS SG1 follow-up for the observation of exoplanet candidates and GAPS, which exploits several telescopes and facilities in Italy (Asiago, OAVdA) and Canary Islands (HARPS-North and GIANO instruments as well as their improved combined version) for exoplanetary characterization.

OPC researchers perform their activity in the framework of collaborations with *Osservatorio Astrofisico di Torino* and *Osservatorio Autonomo della Val d'Aosta*. From July 2017, to date, commissioning observing runs have been done in order to test the telescope and mount capabilities, systematics and limits and to eventually improve the accuracy of the overall system. A software algorithm has been developed[1] in order to estimate the accuracy of any transit observation, so that parameters like the integration time and telescope focus can be chosen to obtain a higher signal to noise ratio, and also to understand the observational limits of the instruments. Currently, the system is able to work within ±1 mmag of accuracy and differential photometry error (refer to the error bars in Figure 6) so that exoplanet transits with ∼5 mmag of relative depth can be observed fruitfully.

The OPC Research Team also aims at the observation of the optical/visible counterpart of gamma ray bursts afterglows, supernovae and GW ToO (Gravitational Waves events / Targets of Opportunity) follow-up along with transiting exoplanets follow-up. The reason is twofold. First of all, the scientific interest on these events of the researchers supporting OPC, and then the demand of the astronomical community for follow-up observations with small telescopes, around the 1-m class, since larger telescopes are often used for primary targets observations. To pursue the target of observing GRBs and the optical counterpart of GW events, it is planned to improve the main instrument accuracy and to develop a consolidated observation procedure, to be ready for the next LIGO-VIRGO O3 run scheduled for the Autumn, 2018.

Keywords: Differential Photometry, Exoplanetary Transits, Algorithm.

Send correspondence to: Luca Naponiello
E-mail: luca.naponiello@stud.unifi.it, Telephone: +39 338 460 8004

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1. INTRODUCTION

The 7-m diameter dome hosts an 80 cm aperture Marcon telescope, but several smaller aperture class instruments and a spectrograph are available at OPC. The main telescope is supported by means of a German equatorial mount from Morales and a gear reducer from Bonfiglioli (Model VF 441F1, ratio 1/35) and its optic design is based on a Ritchey-Chretien configuration. The focal plane can host alternatively two CCD cameras from Moravian Instruments (G2 and G4 models), both managed by means of MaxIm DL control SW from Cyanogen.

Moravian G2-1600 high-quality electronics provides uniform images without artifacts and the readout noise is limited by the CCD detectors themselves. Regulated cooling of CCD up to 50°C below ambient temperature significantly reduces detector dark current. The G2 camera has a resolution of 1536x1024 pixels with 9μm x 9μm area, and is attached to an integrated filter wheel with 5 positions for 1.25" filters in threated cells with a mechanical shutter. The G4 camera adopt a larger CCD detector that has a resolution of 3056x3056 pixels, each with area 12μm x 12μm. Precisely regulated cooling keeps the CCD on constant temperature, which allows quality image calibration. There is a mechanical shutter inside the camera head and an external filter wheel for 50 x 50 mm square filters. The CCD detector is equipped with the so-called anti-blooming gate (ABG), which drains the over-abundant charge from saturated pixels. ABG ensures the round images of bright stars, without disruptive blooming spikes. On the other side, compromising of the CCD linearity by ABG is only negligible. G4 cameras can be used for astrometric and photometric applications as well as for astrophotography.

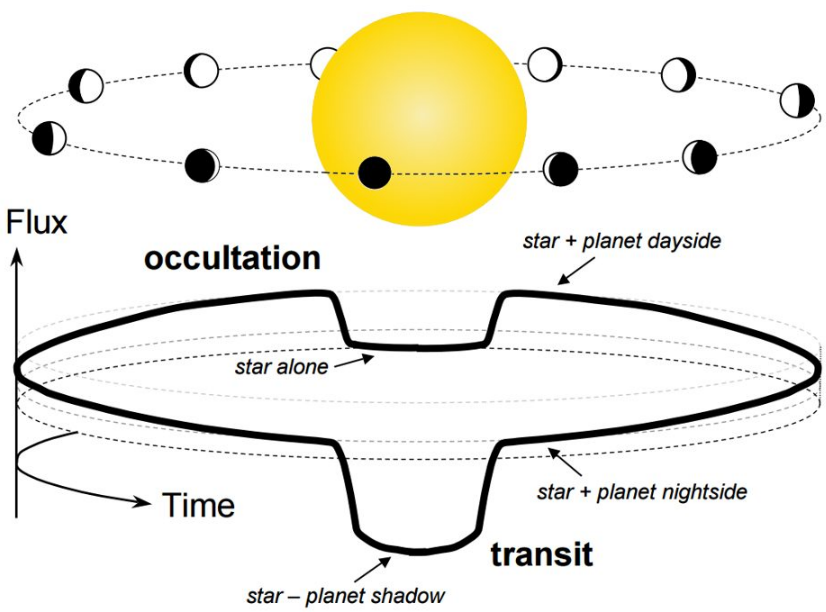

Figure 1. Two transit depths can be appreciated in the image above; the major one happens when the planet moves in front of the star while the smaller one happens when the planet passes behind the star and the former no longer reflects its light towards us.

The transit method is the most efficient for detecting new exoplanets and it is based on the measurement of star flux variations during the planet occultation (as seen in Figure 1). Planetary systems with orbital planes almost parallel to our line of view are the only ones detectable with this method, while big planets that orbit around small stars with a high frequency are easier to find because the transit depth is proportional to the ratio R_p/R_*. Some parameters, other than the planetary radius and the orbital period, can be estimated from transit observations, like the inclination of the orbit, its major axis, and in particular cases even the coefficients that characterize the limb darkening effect. Radial velocity measurements (along with the Rossiter-McLaughlin effect) are then required to further inspect the properties of the planetary system.

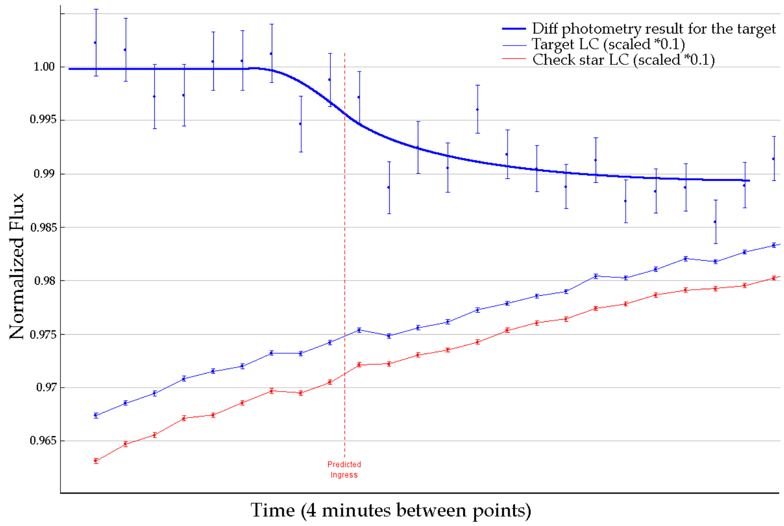

Figure 2. Example of differential photometry for the observation of Kepler-41b. The light curve (LC) on top is obtained by normalizing the blue curve below, using the LC of the reference star in red.

2. ERROR ESTIMATION

In order to be able to see an exoplanetary transit, many pictures of the target star have to be taken and its flux has to be normalized with the flux of constant, reference stars of the same field for each image (Figure 2). That way, the luminosity variations during the observation due to bigger effects like light pollution, change of focus and moonlight disturbance are taken into account. This technique is called differential photometry and it made possible the observation of transits with high S/N ratio even from the Earth.

Each star flux count is affected[2] by the absolute error (in digital units or ADU):

$$N_S \approx \sqrt{\frac{I^*}{G} + n_{pix}\left(1 + \frac{n_{pix}}{n_B}\right)\left(\frac{I_S}{G} + \frac{I_D}{G^2} + \frac{\sigma_r^2}{G^2}\right)} \tag{1}$$

where n_{pix}, n_B are the pixels inside the *aperture* area and the *outer annulus* (see Figure 3) surrounding each star where the sky background luminosity is estimated. I_*, I_S and I_D are respectively the flux of the star, the flux of the background and the dark signal. Finally, G represents the electron/ADU conversion rate of the CCD, or gain, and σ_r the estimated readout noise. Each count error is then propagated to find the error for the normalized flux of the target star:

$$\sigma_{rel.flux} = \frac{F_T}{F_E}\sqrt{\sigma_T^2 + \sigma_E^2} \tag{2}$$

if σ_T and σ_E are the relative errors calculated for the target star and the ensemble of reference stars (including scintillation noise, which is missing in equation 1). Knowing all the parameters of the observation, like the magnitudes of target and reference stars, CCD gain and readout noise, field altitude (i.e. airmass), telescope diameter and average background luminosity, an error expectation can be done for different integration times. Note that a higher integration time requires images to be taken out of focus, this is done to avoid saturating any pixel or going past their linearity limit.

At this point the minimum of the ratio between error and time, in function of integration time itself, points at the focus and integration time that give a higher S/N ratio for the observation. Actually, an higher integration time reduces all noises but the Poisson background noise, because going out of focus reduces the number of pixels that can be used to estimate the sky background luminosity near each star. The integration can't be too high either, otherwise the sampling rate would be too low for the event (known transits usually last between 20 and 200 minutes). An algorithm can be designed to do the estimations for any given transit parameters.

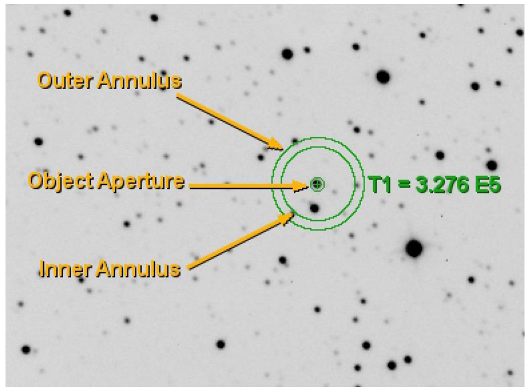

Figure 3. Aperture and outer annulus are the areas where the star flux and background are calculated.

3. ALGORITHM

In Figure 4 the error tendencies are shown for different integration times, highlighting the fact that the seeing noise is the major source of error for the differential photometry of a 7.6 visible magnitude star (HD 189733). The Poisson noise for the background is the limiting factor for the integration time, as previously explained.[1]

When the errors per unit time are combined, one can find the integration time (and telescope focus) that result in a higher S/N ratio (as seen in Figure 5). Note that when the background luminosity is higher than usual, the integration time must decrease because the pixels saturate faster. This algorithm has first been tested with the observation of an easy source, HD 189733b, for different combinations of reference stars, and it has given optimal results. In this case, the estimated error is always within 10% the same one that is found minimizing the χ^2 of the model fit, shown in Figure 6.

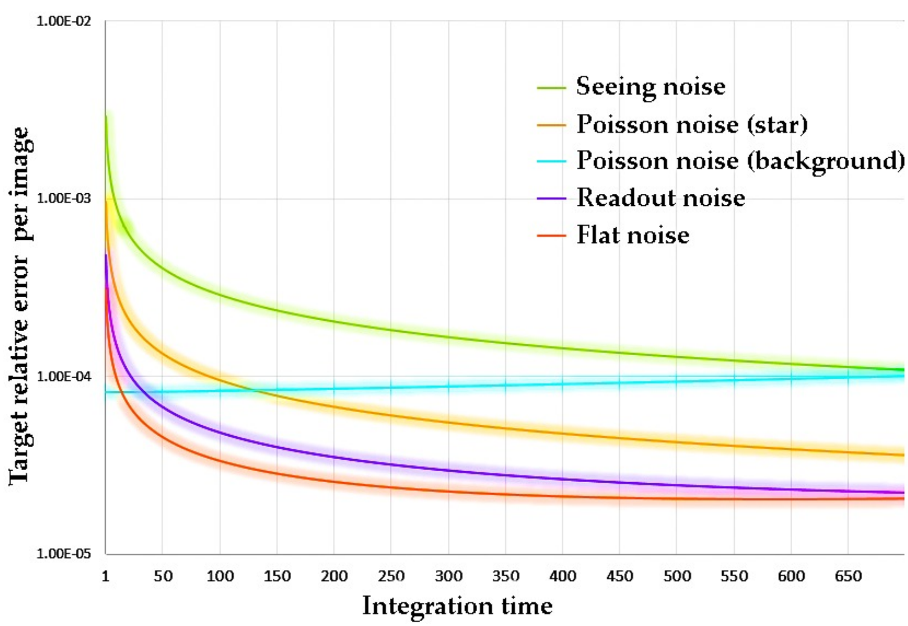

Figure 4. Algorithm's evaluation of major noise sources for the observation of HD 189733b.

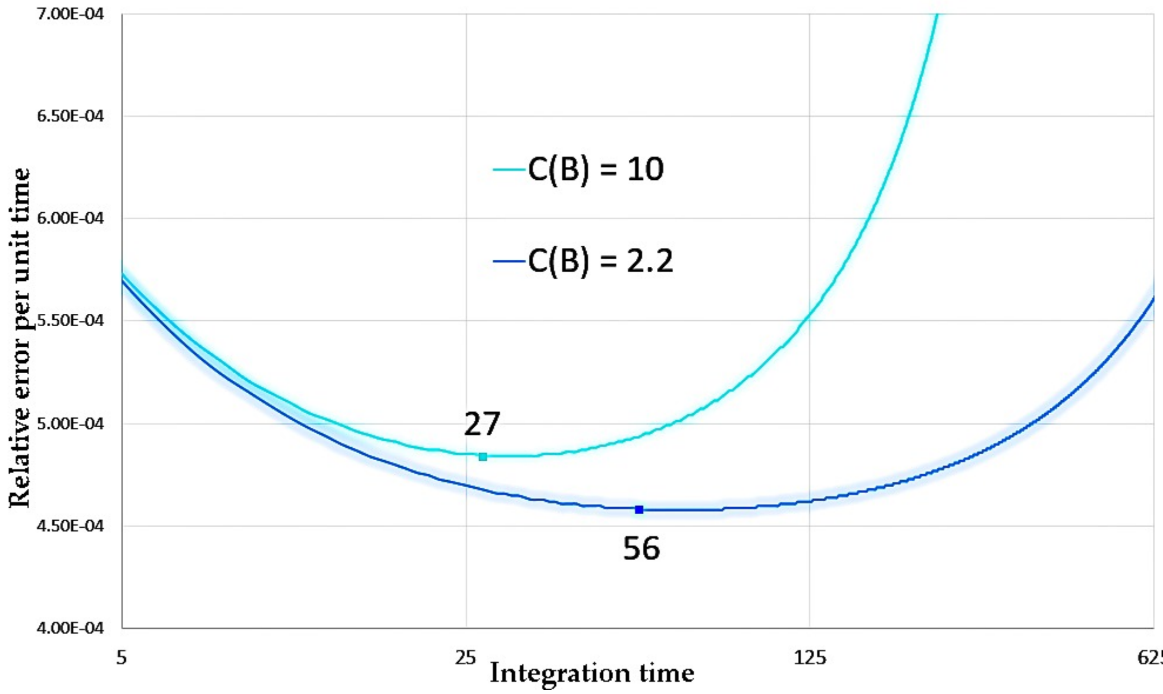

Figure 5. The final error for the normalized target flux is divided by the time unit and plotted in function of the integration time. The minimum represents the integration time that gives a maximum S/N ratio for two different background luminosity coefficients.

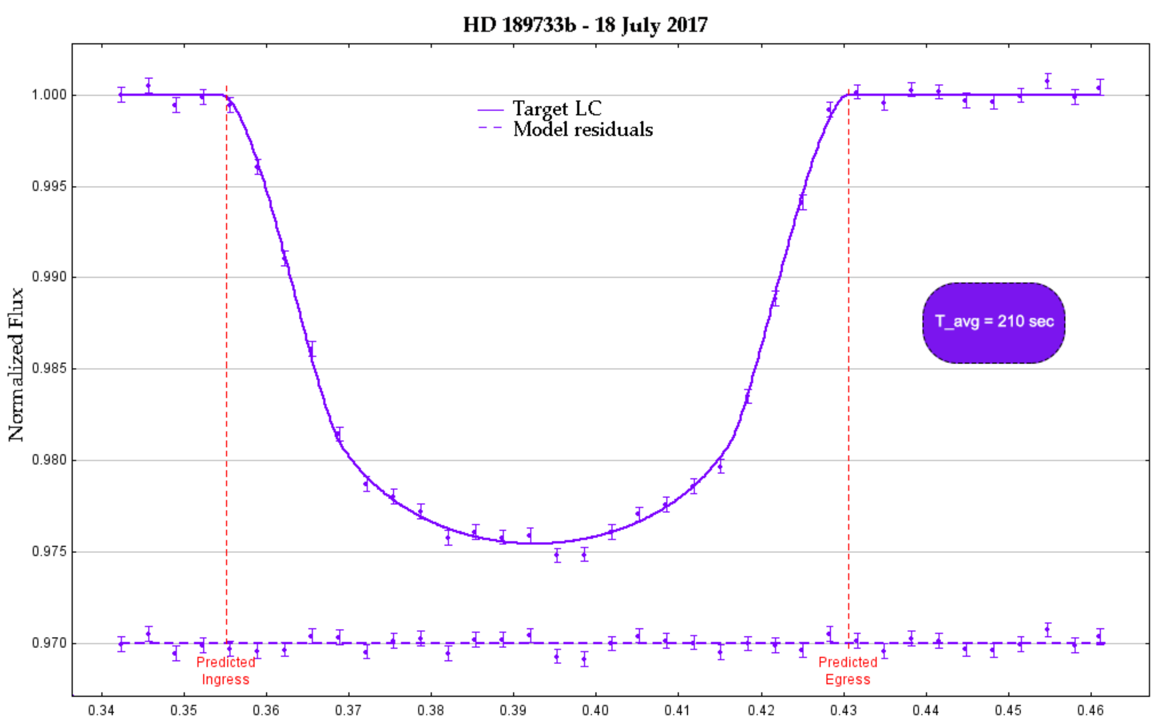

Figure 6. HD189733b transiting exoplanet light curve, as obtained on 18^{th} July 2017. Each point represents a total integration time of 210 seconds. Data has been elaborated with the photometric software AstroImageJ[3] and then the parameter errors have been derived from the MCMC analysis. The radius found is 1.18±0.07 times that of Jupiter.

Now it is possible to make a rough estimation of the observational limit for the OPC setup by studying how the expected error varies with star magnitude and comparing it to star transit depths. In Figure 7 the blue line reflects the area where the estimated error for the normalized star flux is comparable to its transit depth, while near the green line the former is roughly 5 times lower than the latter (note that the error also changes according to sky background luminosity, availability of reference stars and, above all, star altitude during the observation). According to this study, almost 70% of known transits could be studied at OPC, while 20% of them would only be observable with increasing level of difficulty, and the remaining 10% should lie beyond the scope of the instruments.[1]

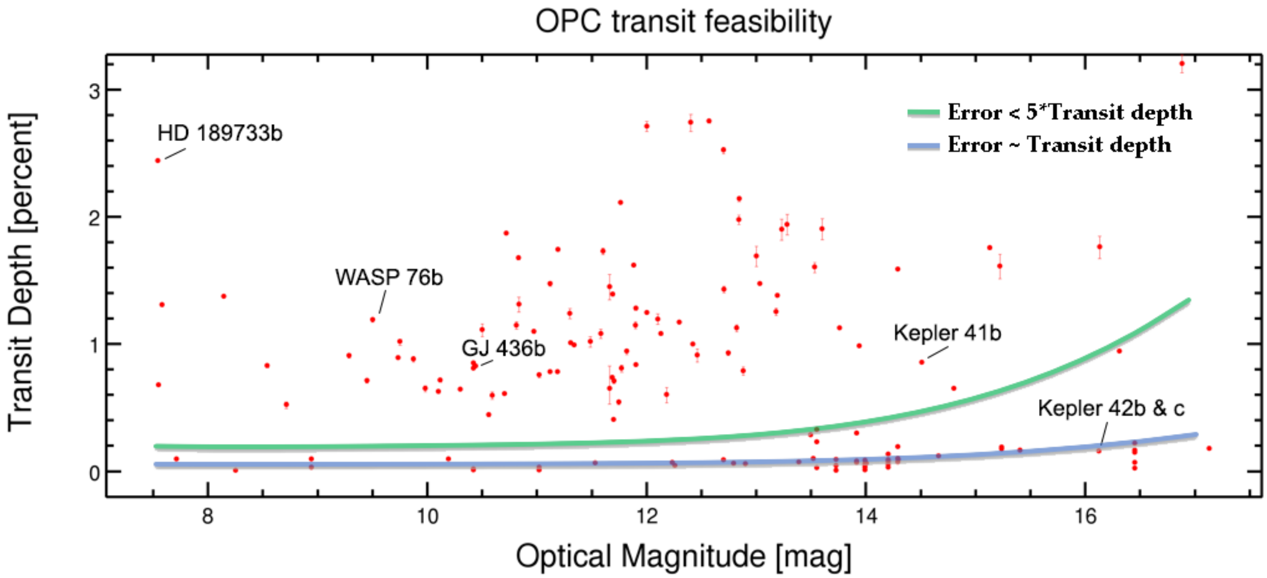

Figure 7. Red dots are stars taken from the NASA archive with certified transits of known depths. The highlighted exoplanets are those that have been observed at OPC during the last 9 months, and all of them confirm the expected S/N ratio.

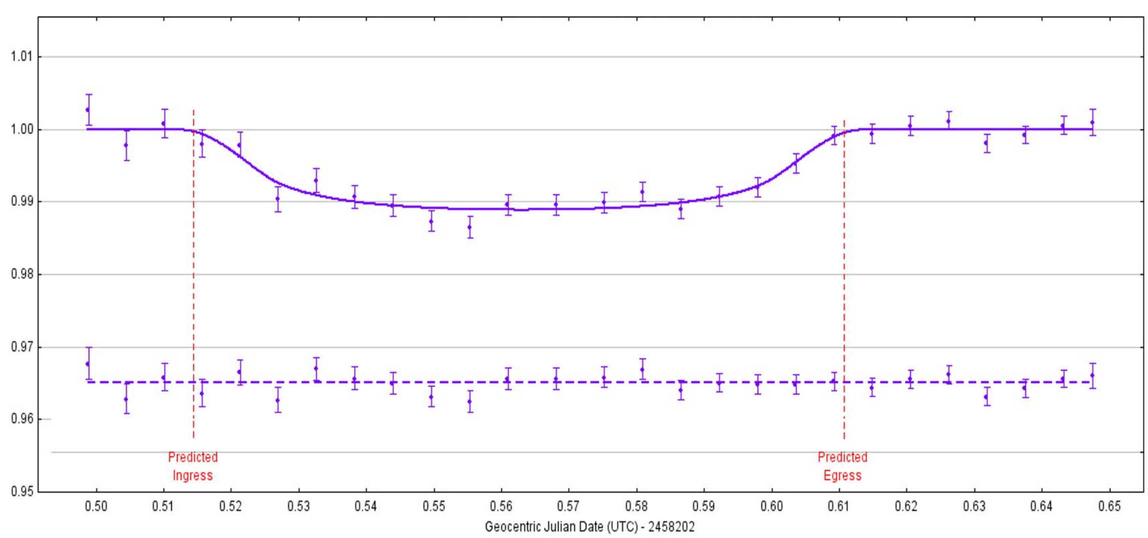

Figure 8. Light curve of Kepler-41b as observed at OPC the 25$^{\text{th}}$ of March 2018 with a low altitude field (30°). Each point represents 480 seconds of exposure and the S/N ratio is getting close to the size of the transit depth as expected.

4. CONCLUSION

This work proved the great capabilities even of small sized telescopes in the field of exoplanetary transits. The transit method is mostly used in space to find new exoplanetary candidates, but then numerous observations have to be made in the following years to find false positives, and most of that contribute can come from the numerous small telescopes on Earth. The OPC will actively be supporting this kind of research as it is doing now with the TESS SG1 team.

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