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Strategies to photometric follow-up transiting exoplanets

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Abstract. It is now well ascertained that those extrasolar planets that transit in front to their parent stars deserve extensive follow-up observations because they are the only ones for which we can directly measure all their physical parameters. This information currently provides the best route to constructing the mass-radius diagram of exoplanets, which channels the theoretical formation/evolution models in the right path. However, many of the discovered transiting planets do not have high-quality light curves, so their physical properties are poorly known. In this perspective, we are leading a large program to obtain ultra-high-precision photometry of transit events, which are analyzed to accurately measure the physical properties of know planetary systems. Besides measuring and refining the physical properties of the planets and their parent stars, we also try to obtain additional information from the light curves, by identifying particular features of the systems (e.g. stellar activity) and investigating the composition of the planetary atmospheres by transmission photometry. In this conference-proceedings contribution I present several observational strategies that we adopt to achieve these goals.

Key words: stars: planetary systems – stars: fundamental parameters – techniques: photometric

1. Introduction

The first detection of a planet orbiting a main-sequence star (51 Peg; Mayor & Queloz, 1995) started a new era of astronomy and planetary sciences and raised expectations of finding an Earth-twin in the near future. Since that time, the efforts to find new extrasolar planets have steadily increased and, at present, more than 900 extrasolar planets in roughly 700 planetary systems have been confirmed. Among all the extrasolar planets, those that transit their parent stars are of the greatest interest and importance, because for only these it is possible to achieve accurate measurements of their physical and atmospheric properties by combining spectroscopic and photometric data. Transiting extrasolar planets (TEPs) have provided myriad of fascinating surprises and puzzles since their discovery, thus opening a new branch of astrophysics. The increasing number of TEPs discovered is progressively revealing a remarkable diversity. The improving statistical weight of this sample is the most promising avenue for establishing the correct theoretical framework of planet formation and evolution. Accurate estimates of the planet properties (mass, radius, orbital semi-major axis, etc.) are vital for this purpose, and photometric studies of TEPs are not only fundamental to confirm their planetary nature, but can dramatically improve our knowledge of the planets' characteristics.

2. Accurate properties of extrasolar planets via telescope defocussing

At present many of the 365 known TEPs do not have high-quality follow-up light curves, and so their properties were not measured with a very good accuracy. We are therefore conducting a long-term project to observe these objects with an array of medium-class telescopes from both the hemispheres. This project is running in survey style: we require a substantial investment of telescope time in order to obtain publishable results for a large number of objects (i.e. Southworth et al., 2010, 2011, 2012a,b,c, 2013; Mancini, et al. 2013a,b,c; Ciceri, et al. 2013; Harpsøe et al., 2013; Nikolov et al., 2013; Maciejewski et al., 2013; Covino et al., 2013).

Our strategy is to obtain ultra-high-precision differential photometry of complete transit events of TEP systems, which will be analyzed to measure the physical properties of planets and their parent stars. The observations are performed using the *telescope-defocussing method*, where the telescope is defocussed and long exposure times (up to 120 s) are used. This causes the observational efficiency to be high as the CCD is read out less often, thus minimizing Poisson and scintillation noise. The large PSFs are also insensitive to focus or seeing changes, which could otherwise cause systematic errors. The other main source of systematic error, flat-fielding, is decreased by two orders of magnitude as each PSF covers thousands of pixels. Telescope pointing errors affect photometry via flat-fielding errors, so these also average down to very low levels. The defocussing approach was pioneered using the Danish 1.54-m telescope at La Silla (Southworth et al., 2009a,b) and is now become a standard technique. With telescope defocussing is possible to achieve light curves of remarkable precision (down to 10^{-4}) and thus measure the radii and the masses (by using theoretical stellar evolutionary models) of TEPs to accuracies of $1-3\%$. The two parameters, defocus and exposure time, are set each night considering the weather conditions, the dimension of the telescope, the brightness of the target star, the filter chosen for the observation, and the possible presence of nearby stars, which can produce blending effects. For example in Fig. 1 we report high-precision photometric data of a planetary transit of Qatar-1 b obtained with the 1.23-m telescope at the German-Spanish Astronomical Center at Calar Alto in Spain. We heavily defocus the telescope and used an exposure of 120 s. The corresponding light curve has a point-to-point scatter around the JKTEBOP[1] best-fitting model of 0.78 mmag (Covino et al., 2013).

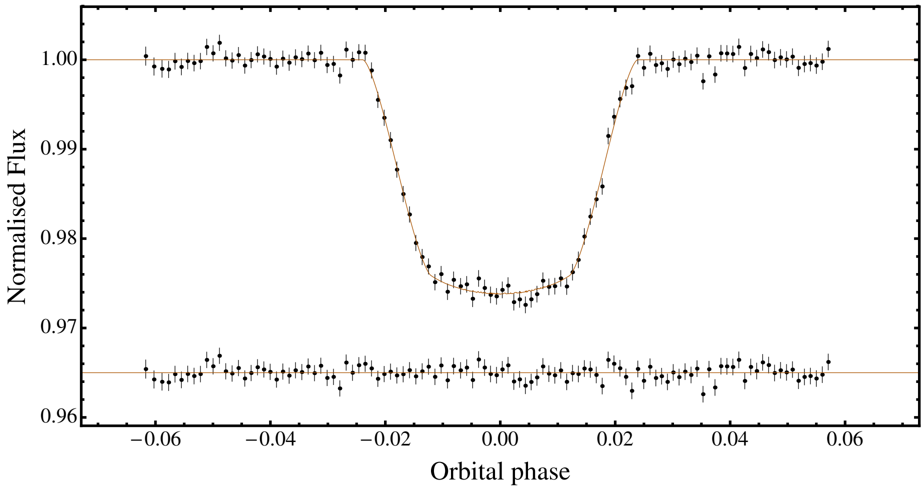

Figure 1. A high-precision phased light curve of a planetary transit of Qatar-2 b observed through a Cousins-R filter and compared to the best fit found using JKTEBOP. The residuals of the fit are plotted at the bottom of the figure. The light curve has a scatter around the best-fitting model of 0.78 mmag. The parent star is a $V = 12.8$ mag K dwarf (Covino et al., 2013).

3. Two-site observations of planetary transits

Accurate photometric monitoring of transit events can highlight anomalies in the light curves which have astrophysical origins. The detection of starspots[2], occulted by TEPs during their transits, is indeed becoming more and more frequent in the last years (e.g. Pont et al., 2007; Rabus et al., 2009; Silva-Valio et al., 2010; Désert et al., 2011; Sanchis-Ojeda et al., 2011; Sanchis-Ojeda & Winn, 2011b; Tregloan-Reed et al., 2013; Mohler-Fischer et al., 2013; Mancini et al., 2013c). However, in case of ground-based observations with medium-class telescopes, the identification of a true signal from systematic and atmospheric noise is always a difficult task, especially when the transit depth is lower than

[1]The JKTEBOP code is used to fit a model to the light curves of TEP systems. It is available at http://www.astro.keele.ac.uk/jkt/codes/jktebop.html

[2]The strategy to use classical in-focus observations, with short exposure times, and then bin the data to reduce the scatter of the points in the light curves, keeps out the possibility to detect starspots.

2%. A method to discriminate between instrumental/environmental noise and astrophysical signal is to have independent measures of the same transit event by using two telescopes located at two different observatories. The latter fact is important in order to avoid that the two monitorings are affected by the same weather-condition variability. So, if both the telescopes detect the same anomaly, we can be more confident that we are observing an astrophysical phenomenon. By using the Cassini 1.52-m telescope at the Astronomical Observatory of Bologna in Italy and again the CAHA 1.23-m telescope in Spain, this two-site observational strategy was successfully tested to follow-up HAT-P-8 (Fig. 2), where an anomalous asymmetry with respect to the line of minimum transit time was detected in both the light curves (see Mancini et al., 2013a for details) and then used for the cases of HAT-P-16 and WASP-21 (Ciceri et al., 2013), but in these two cases the simultaneous observations did not highlight particular features in the light curves. In a case reported by Lendl et al. (2013), this method was very useful to exclude the spot hypothesis of a light-curve anomaly detected in a photometric follow-up of WASP-19.

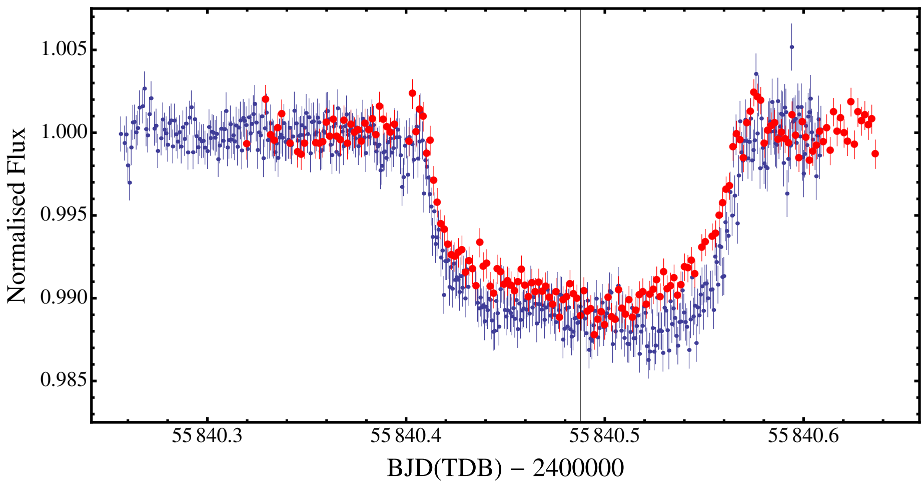

Figure 2. Two-site photometric follow-up observations of a planetary transit of HAT-P-8 b. Blue dots are for the data taken with the 1.52-m Cassini telescope, whereas the red ones for those taken with the CAHA 1.23-m telescope. Some of the difference in depth between the two datasets are due to different filters used, Gunn i and Cousins R, respectively. The vertical line represents the expected transit mid-point. The parent star is a $V = 10.3$ mag F8 star (Mancini et al., 2013a).

4. Multi-band observations of planetary transits

Another fascinating use of precise photometric observations of planetary transits is the possibility to probe the chemical composition of the atmosphere of TEPs in a way similar to transmission spectroscopy. Indeed, planets' atmospheres are transparent at some wavelengths and opaque at others. So, during a planetary transit, the light coming from the parent star can be absorbed (or scattered) at specific wavelengths according to the amount and density of absorber atoms and molecules (like hydrogen, helium, water, methane, carbon monoxide, etc.) present in the atmosphere of the TEP. Therefore, the idea is to observe planetary transits through different filters, each covering a different region of the electromagnetic spectrum, and measure a possible variation of the planet radius as a function of the wavelength. Thanks to the differential photometry, this technique is much less affected by variations in telluric transparency than single-slit transmission spectroscopy performed by the ground. Moreover, parent-star activity in the form of large starspots on its photosphere can be easily detected and modelled with photometric observations in the optical bands. Another advantage is the possibility to study the atmosphere of TEPs orbiting faint stars, whereas transmission spectroscopy is a technique limited only to bright stars and requires high-resolution cryogenic spectrographs on large-aperture telescopes or medium-resolution spectrographs on space telescopes.

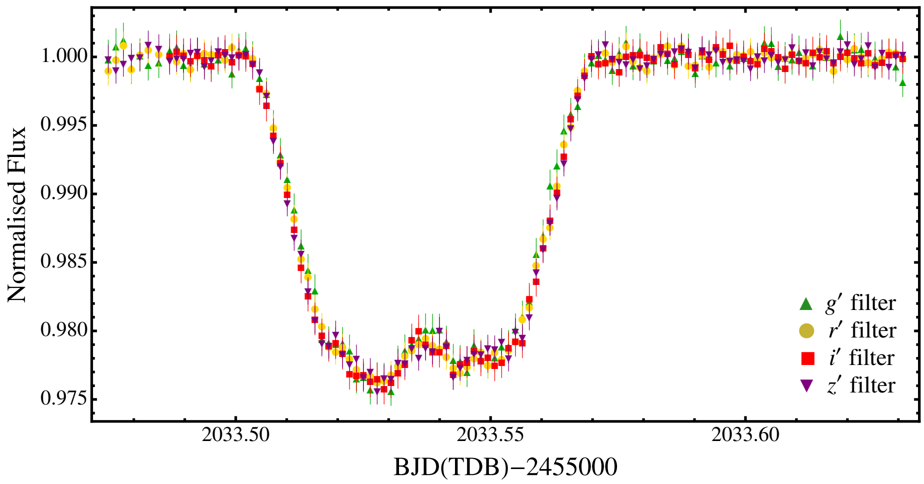

Figure 3. Combined four-colour transit light curves of a planetary transit of WASP-19 b obtained with GROND. The bump observed just around the midtransit is interpreted as the covering of a starspot by the planet. The parent star is a $V = 12.3$ mag G8V star (Mancini et al., 2013c).

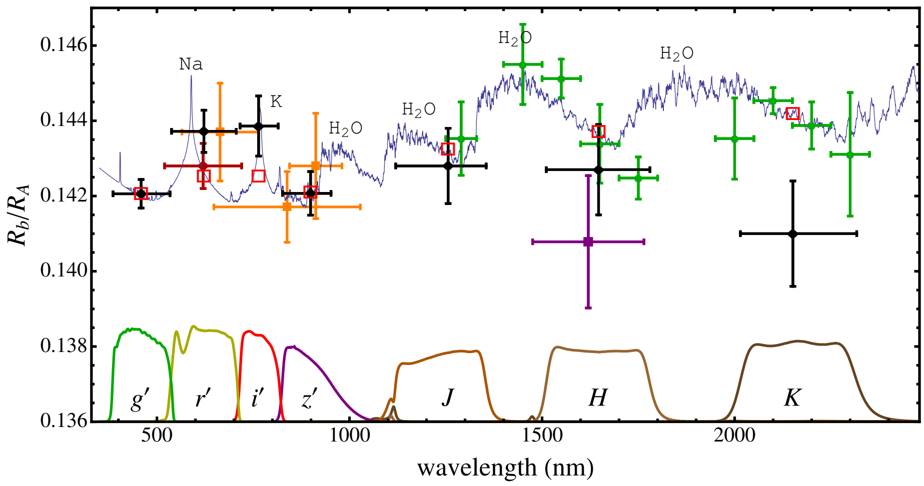

Figure 4. Variation of WASP-19 b's planetary radius with wavelength. Black points are from GROND, the other colored points are from literature. Red open boxes indicate the predicted values for the model integrated over the passbands of the observations. Transmission curves of the GROND filters are shown at the bottom of each panel. Prominent absorption features are labelled (Mancini et al., 2013c).

Transmission photometry can be obtained by different telescopes at different times (de Mooij et al. 2012; Fukui et al., 2013). However, considering possible changing of the sky transparency and intrinsic variability due to activity of the target or reference stars, it is always better to perform multi-band observations simultaneously with only one telescope – instrumental systematics can indeed produce difference in the transit depth which can be not colour depending (Lendl et al., 2013). Simultaneous multi-band observations of planetary transits were recently obtained for several TEP systems by using multi-band imaging detectors like the "Bonn University Simultaneous CAmera" (BUSCA) mounted at the CAHA 2.2-m telescope (Southworth et al., 2012b; Mancini et al. 2013a), the "Gamma Ray Burst Optical and Near- Infrared Detector" (GROND) mounted at the MPG/ESO 2.2-m telescope (Mancini et al., 2013b, 2013c; Nikolov et al., 2013; Penev et al., 2013; Mohler-Fisher et al., 2013; Bayliss et al., 2013) and the PI instrument ULTRACAM (Copperwheat et al., 2013).

An example of simultaneous multi-band observations is shown in Fig. 3, where a planetary transit of WASP-19 b was monitored with GROND through four filters similar to Sloan g', r', i', z'. A clear anomaly, due to a starspot, is visible in all the four optical bands close to the midpoint of the transit. Thanks to these data, it was possible to look for a variation of the radius of WASP-19 b with wavelength. This is shown in Fig. 4 in terms of planet/star radius ratio, $R_{\rm b}/R_{\rm A}$. The vertical bars represent the errors in the measurements and the horizontal bars show the full widths at half maximum transmission of the passbands used. The experimental points are compared with a synthetic spectrum that does not include TiO and VO opacity. The atmosphere of WASP-19b turns out to be dominated by absorption by H_2O, Na, and K, and no evidence for a strong optical absorber at low pressure, which agrees well with the fact that WASP-19 b's atmosphere lacks a dayside inversion (Mancini et al., 2013).

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