Looking for Exoplanets in Bright Stars with Small Field-of-View Detectors

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Abstract

Differential photometry is a robust technique for ground-based observations of transits since it sorts out slow variations of sky transparency as well as other first order effects that are common to all stars in the field-of-view (FOV) of the imaging detector. To work properly, differential photometry has to obey a few requirements like similar brightness of the target and reference stars, similar colors and a relative proximity in the plane of the sky to avoid sensitivity variations like those caused by vignetting. It happens that for bright stars these conditions are hardly met. Typical CCDs in a ~60 cm class telescope give a FOV of ~10 arcmin and this is not enough to have suitable reference stars in the same image frame. Also, bright (V < 7) stars tend to saturate the detector for the shortest practical integration times. To minimize these problems, we tested an instrumental setup in which half of the detector is covered with a neutral density (D=2.3) filter. We report CCD observations on which we achieved mmag precision for bright systems that are not known to show transits, like τ Boo, 55 Cnc and HD162020, as well as the known case of HD209458.

Introduction

The most precise method to measure photometric variations of stars from ground-based observations is the Differential Photometry (DP) in which we measure the flux ratio (or difference of magnitudes) between the target (variable) and comparison stars on the same field. The flux ratio R is given by

$$R \pm \sigma_R = \frac{F_V \pm \sigma_V}{F_C \pm \sigma_C}$$

where F_V and F_C are the fluxes of the variable and comparison stars and σ_V and σ_C are their respective individual errors. By propagating the errors, we can write the relative variance of R,

$$\left(\frac{\sigma_R}{R}\right)^2 = \left(\frac{\sigma_V}{F_V}\right)^2 + \left(\frac{\sigma_C}{F_C}\right)^2 - 2\frac{\sigma_{VC}{}^2}{F_V F_C}$$

Therefore we can see that the relative error on the measurement of the ratio R depends on the errors of the individual fluxes. Then, to obtain suitable measurements of this ratio we have to chose comparison stars that are at least as bright as the target star, otherwise our precision would be limited by the errors from the comparison star. Based on this, we describe below some requirements for a good choice of the comparison star:

✓ **Comparable brightness:** the comparison star should have at least the same photon counts as the target star.

✓ **Color similarity (same spectral type):** to keep as close as possible the ratio of variations between the stars due to differential extinction and other color effects.

✓ **Proximity on the plane of the sky:** to minimize effects due to different airmasses and variations of sensitivity such as those due to vignetting.

For a bright target (V ≤ 7 mag) we hardly meet all these requirements, since for short integration times, necessary to keep counts far from detector saturation, rarely we have a comparison star as bright as the target star on the same FOV. The way we found to avoid this problem was to assemble a neutral density filter covering half the detector. This allows simultaneous measurements of stars with very different brightness levels.

Experimental arrangement

We placed the (bright) target star on the covered part of the detector, and this allows longer integration times. In the open half of the detector, fainter stars suitable to be used as comparison objects show up. We used a neutral density filter with D=2.3, equivalent to an attenuation of ~5.7 magnitudes. In other words, a 7 mag star would appear as a ~12.7 mag star, and any objects similar or brighter than this would be adequate as comparisons. In fact, most of the time we obtain several objects suitable for use as comparison stars. Their individual fluxes can be combined to produce an "ensemble" comparison star.
A few more details about the experimental setup:

Filter position: from a previous analysis of the FOV around the candidate targets, the optimal position of the density filter was chosen. One important constraint is not placing the filter in the downstream direction of the CCD readout. Figure 1 illustrates the setup for the field around 55 Cnc.

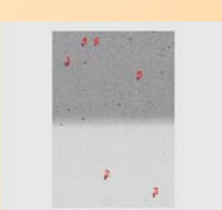

Figure 1: Image of the field of 55 Cnc. The covered region is down and the free region up. The labeled stars are: 1 – main comparison, 2 - 55 Cnc, 3, 4, 5 e 6 – other comparison stars.

Exposure time: the choice of optimal exposure time is done as usual, examining the radial profile and peak counts, and paying attention to factor ~200 attenuation in the case of using an observatory-provided calculator for exposure time!

Focusing: it is a common practice to use defocusing to avoid saturation. In our case, the important point is to have good focus in the clear region of the detector. A slight defocus in the covered region is perfectly dealt with in the photometry extraction stage.

Flat-field: this is an important issue, since for a given integration time the covered and open parts of the detector receive a flux that is a factor of ~200 in intensity. The best strategy is to take two groups of images with different exposure times, to normalize the relevant part and to subsequently combine them in a single master frame.

Instrumentation: we show below a summary of the instrumentation we used at the Pico dos Dias Observatory of the National Laboratory of Astrophysics (OPD/LNA), in Brazil:

Description of the instrumentation	
Telescopes	0.6 m Ritchey-Chrétien - Boller & Chivens 0.6 m Cassegrain – Zeiss
Filters	Neutral filter (D=2.3) and color filter (I_C-band)
Effective focal ratio	f/13.5 f/12.5
CCD (106)	Thin, "back-illuminated", 1024x1024 pixels
Field of view	~10' x 10'

Table 1: Description of the instrumentation.

Data reduction

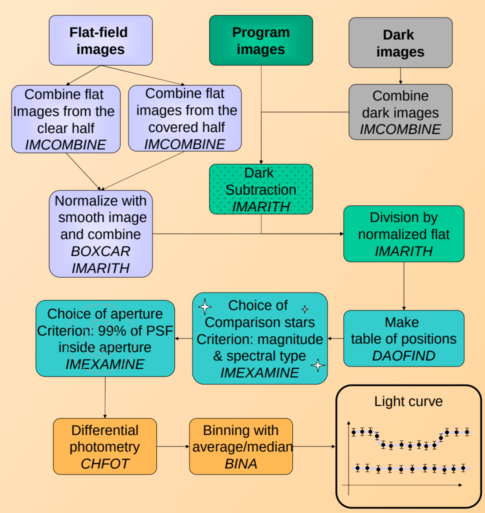

Figure 2: Flowchart showing the steps for our data reduction carried out under IRAF environment.

The data reduction was carried out under IRAF and consists of standard procedures shown in the diagram of Figure 2.

The flux extraction was done with an IRAF script called *chfot*. This task automatically subtracts dark/bias and divide program images by the normalized flat-field images; it identifies the stars in each frame, centers precisely in each object, extracts the correspondent fluxes, calculates the magnitude differences and presents the data together with heliocentric julian date. An useful feature of the program is to be able to add up all the comparison stars. This is important in cases in which the variable object is the brightest in the field-of-view even after it has been attenuated.

Results

We present below the photometric results of an application of our technique obtained for three bright stars that are known to have exoplanets detected by spectroscopic radial velocity measurements, but not known to have transits. The systems are 55 Cnc, τ Boo and HD 162020.

LOG of the observations						
Star	Date	V (mag)	RMS (mag)	N points	t_{exp} (s)	Δt (s)
55 Cnc	07Mar2005	5.95	0.006	199	20	47
55 Cnc	08Mar2005	5.95	0.009	318	10	32
55 Cnc	09Mar2005	5.95	0.01	299	10	38
τ Boo	07Mar2005	4.5	0.02	170	30	58
τ Boo	08Mar2005	4.5	0.007	397	10	34
τ Boo (binned)	08Mar2005	4.5	0.003	57	-	240
HD 162020	09Mar2005	9.18	0.007	100	30	42

Table 2: Log table of the observations carried out on March 07, 08 and 09, 2005, in which we have used the differential photometry technique described on the text. The RMS and Δt values represent the photometric precision (in magnitudes) and sampling time (in seconds) respectively.

Among the results on Table 2, the best conditions were met for τ Boo, for which we show on Figure 3 the resulting light curve and the respective error bars. These data show a rms deviation of 0.003 mag which means that we would be able to detect a photometric transit at this level or slightly lower. We also show superimposed on the data two simplified simulations of the known transits in HD 209458 and HD 189733.

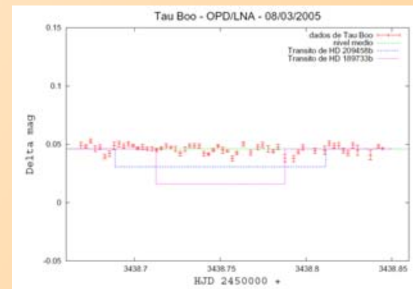

Figure 3: Tau Boo data averaged at every 7 points (red dots + error bars). The simplified transit light curves of HD209458 (blue dotted line) and HD189733 (magenta dashed line) are shown for comparison.

We notice from Figure 3 that transits similar to those shown by HD 209458 and HD 189733 would be easily detected in our photometry. In other words, the method should work well for giant planets around bright stars. In order to test in practice the technique, we also made observations of a transit in HD209458, and we show the results in the following section.

The transit of HD 209458 b

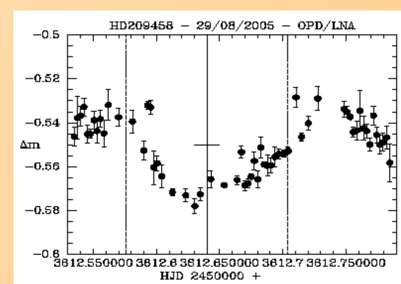

Figura 4: HD 209458 data averaged every 5 points. The estimated photometric error is below 0.01 mag. The vertical lines are the predicted times for ingress, egress and central time of the transit.

The results shown in Figure 4 clearly show the transit with a noise level below 1%. We also can get the transit parameters, such as the central instant and depth. Although the results can be considered satisfactory, they could be better, since the observations were carried out in non-ideal weather conditions.

Conclusions

➢ We developed a straightforward technique to make mmag precision differential photometry aiming to monitor bright stars that potentially could show exoplanetary transits.

➢ We present a methodology for applying this technique to 60-cm class telescopes. We obtained results comparable to those in Lopez-Morales et al. 2005 for 1-m telescopes.

➢ We tested the technique by monitoring three bright stars: 55 Cnc, HD 162020 e τ Boo, and for the latter we obtained the best results with a photometric rms of 0.003 mag during ~4 hours. This would be enough to detect transits of giant planets in close orbits.

➢ We also tested the technique on the well known transit of HD209458b where we obtained a photometric precision below the required 1.6% to detect the event. The data allows one to estimate the main transit parameters, namely, central time of the event and its depth.

Bibliography

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