A modified *CoRoT* detrend algorithm and the discovery of a new planetary companion

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ABSTRACT

We present MCDA, a modification of the CONvection ROTation and planetary Transits (*CoRoT*) detrend algorithm (CDA) suitable to detrend chromatic light curves. By means of robust statistics and better handling of short-term variability, the implementation decreases the systematic light-curve variations and improves the detection of exoplanets when compared with the original algorithm. All *CoRoT* chromatic light curves (a total of 65 655) were analysed with our algorithm. Dozens of new transit candidates and all previously known *CoRoT* exoplanets were rediscovered in those light curves using a box-fitting algorithm. For three of the new cases, spectroscopic measurements of the candidates' host stars were retrieved from the ESO Science Archive Facility and used to calculate stellar parameters and, in the best cases, radial velocities. In addition to our improved detrend technique, we announce the discovery of a planet that orbits a $0.79^{+0.08}_{-0.09} R_{\odot}$ star with a period of 6.71837 ± 0.00001 d and has $0.57^{+0.06}_{-0.05} R_J$ and $0.15 \pm 0.10 M_J$. We also present the analysis of two cases in which parameters found suggest the existence of possible planetary companions.

Key words: methods: data analysis – planets and satellites: detection – stars: fundamental parameters.

1 INTRODUCTION

Stellar light curves may carry intrinsically long-term trends which are associated with the variability in the stellar flux itself. Other sources of trends appear from space-based photometry measurements as systematic variations requiring special analysis to optimize, for instance, planetary transit detections. Earth-like planets demand high-quality measurements since the transit generates variations in the flux measurements of, at most, a few per cent. Moreover, in order to perform the best assessment of the data, we must be able to deal in the best possible way with the presence of intrinsic stellar variability as well as systematic trends caused by the influence of external error sources. Usually detrend techniques are performed combining mathematical and statistical operations, and their design is closely related to the chosen detection method as discussed by Moutou et al. (2005), Aigrain & Irwin (2004) and Mislis

et al. (2010). For a better understanding of light curves detrending problems, see Mazeh, Tamuz & Zucker (2007), Ofir et al. (2010), Kovács & Bakos (2008) and Kim et al. (2009).

*CoRoT*¹ (CONvection ROTation and planetary Transits) was a space-based mission focused on precise photometric measurements, allowing both stellar seismology analysis and the detection of new exoplanets by means of the transit method (Auvergne et al. 2009). It consisted of a 27 cm telescope equipped with four CCD cameras in two different fields, one for each main scientific goal, seismology channel (bright stars) and exoplanet channel (faint stars). The *CoRoT* public data set is composed of tens of thousands of light curves obtained in the chromatic or monochromatic mode and was assembled from 2007 January to 2012 November by means of short (SR) and long runs (LR). The pointing targets in this mission were

¹ The *CoRoT* space mission, launched on 2006 December 27, was developed and is operated by the CNES, with participation of the Science Programme of ESA, ESA's RSSD, Austria, Belgium, Brazil, Germany and Spain.

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chosen within two main regions in the sky, one towards the Galactic Centre (LRc or SRc, $\alpha = 18^{\text{h}}50^{\text{m}}$) and the other towards the Galactic Centre anticentre (LRa or SRa, $\alpha = 06^{\text{h}}50^{\text{m}}$). Most stars monitored in the faint stars field were primarily sampled at a 512 s rate. Up to 2000 stars could also be monitored at a 32 s rate when triggered the so-called alarm mode (Surace et al. 2008; Bonomo et al. 2012). The original field coverage comprising the exoplanet channel during each pointing was about $1.4 \times 2.8 \text{ deg}^2$, allowing CoRoT to observe up to 12 000 stars per run.

In this work, we present a modification to the CoRoT detrend algorithm (CDA) (Mislis et al. 2010). Our detrend filtering technique focuses on the treatment of sudden statistical fluctuations, a feature that strongly affects folding phase transit search methods. Mislis et al. (2010) found for the chromatic (CHR) light curves in CoRoT Initial Run IRa01 that less than 1 per cent of this type of event appear in the three colour channels simultaneously. So, this technique uses a comparison obtained in each colour channel individually to attenuate the presence of discontinuities.

All CHR CoRoT light curves – 65 655 in total – were analysed in this work with our algorithm. All CoRoT previously known exoplanets in those light curves were found and new candidates appeared. In Section 2, we describe our algorithm, its performance and validation. Section 3 describes the photometric data, the transit detections and modelling, and Section 4 the spectroscopy analysis for the found new candidates. The results are presented in Section 5 and our conclusions in Section 6.

2 ALGORITHM

2.1 Description

Mislis et al. (2010) developed a technique to detrend CoRoT light curves from sudden intensity changes. Such changes can be of stellar activity origin, although the vast majority are clearly instrumental in nature (Pinheiro da Silva et al. 2008) and strongly affect folding phase transit search methods. Although space-based telescopes can provide high-precision stellar measurements due to the lack of atmosphere, there are other sources of error to deal with. The measurements provided by the CoRoT satellite detectors frequently suffer with the presence of spurious charge added to the integrated stellar flux as estimated by Mislis et al. (2010). It is primarily the result of the impact of highly energized particles that overcame the protective shielding on to the detectors. Pinheiro da Silva et al. (2008) showed that in the CoRoT case, this phenomenon is closely related to the satellite’s low Earth orbit since these particles are originated from the interactions of cosmic rays in the Earth’s upper atmosphere. Indeed, the passage over the South Atlantic Anomaly produces the highest rate of radiation. These sudden variations in the data, commonly referred to as ‘jumps’ in the literature, can be a transitory damage, suffering decay after a while, or they can generate a permanent bright pixel when the impact alters fundamental properties of the sensor.

Our main goal is to improve the algorithm sensibility in the presence of discontinuities. Therefore, our main modifications of the CDA algorithm are as following.

(1) We replaced the originally employed third-order polynomial fit with a resistant moving average. So, the mean value of the light-curve section is taken with respect to its central value with an equal number of measurements on either sides,

$$\overline{\text{MA}} = \frac{x_m + x_{m-1} + \dots + x_{m-(n-1)}}{n}, \quad (1)$$

where n is an arbitrary value with respect to the sampling. At this point, care should be taken to avoid overlapping the boxcar size with the typical transit durations as well as to minimize attenuation. In the case of the CoRoT data, one expects transits up to around 5 h. Additionally, high-frequency signals are not filtered out.

(2) In order to deal with the most significant jumps and to minimize the local statistical error propagation (which are method dependent) in the final results, we implemented a robust statistics rather than the one adopted by Mislis et al. (2010). At first, we separated the measurements of the three channels into three independent light curves. This colour decomposition, here informally designated as red, green and blue channels (R, G, B), was obtained reading out the split regions within each stellar mask on the CCD, according to the spread of the white light. Each set was then divided into subsets with 1 d length. A normalization using the resistant mean for each subset i was performed

$$[R', G', B']_i = \frac{[R, G, B]_i}{\bar{x}_{\text{res}[R, G, B]}}. \quad (2)$$

For each colour set, we randomly selected five subsets and computed the mean resistant standard deviation

$$\bar{\sigma}_{\text{res}[R', G', B']} = \frac{1}{5} \sum_{i=1}^5 \sqrt{\frac{1}{l-1} \sum_{j=k_i}^{k_i+l} ([R', G', B']_j - \bar{x}_{\text{res}[R, G, B]_i})^2}, \quad (3)$$

where i is regarded to each subset, j to each element within the subsets and l to the number of elements in the subset. The normalized subsets allow us to do direct comparisons regarding statistical inference among the three channels. Also, we need to assess the significance of each $\bar{\sigma}_{\text{res}}$ relative to the light curve as a whole, i.e. estimate the presence of considerable statistical variation on each colour. To do so, we first compute the resistant standard deviation of each colour set

$$\sigma_{\text{res}[R', G', B']} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n ([R', G', B']_i - \bar{x}_{\text{res}[R, G, B]})^2}, \quad (4)$$

where n is the set of elements which lie within the sigma cut established in our robust analysis. We compute then the relative deviations of each colour set to determine in which set the highest deviation is located,

$$\sigma_{\text{rel}[R', G', B']} = \frac{\sigma_{\text{res}[R', G', B']}}{\sigma_{\text{res}[R', G', B']}} \quad (5)$$

Finally, the relative deviations in each colour are ranked and the channel with the highest deviation is replaced by the average value of the channels with the highest and lowest deviations as follows:

$$C_{\text{corr}} = \frac{C_{\text{high}\sigma_{\text{rel}}} + C_{\text{low}\sigma_{\text{rel}}}}{2}. \quad (6)$$

This procedure is repeated in a loop while the relative deviations decrease relative to the former ones. After that, no significant statistical information can be used to reduce the presence of jumps.

2.2 Performance and validation

2.2.1 Application to real data

We now show the performance of our technique using the data provided by the CoRoT mission. The light curves were obtained from the IAS CoRoT Public Archive. The data we used from the

Figure 1. Comparison between the original flux observed with the *CoRoT* satellite and the results of the applied detrends methods discussed in Section 2. At the top, a *CoRoT* light curve shows the presence of discontinuities in the original normalized flux. The middle shows the light curve detrended using the CDA algorithm. The bottom shows the correction using the MCDA method described in this work.

Figure 2. In the top figure, we show the median of absolute deviations from the median (MAD) of each light curve for the LRA01 run after detrending the data using the CDA described in Mislis et al. (2010) against the MAD of the raw data set. The bottom figure exhibits the MAD results using our method. It is noticeable that the MCDA provides a higher reduction in the statistical dispersion originated from jumps and stellar variability.

initial runs were processed with pipeline version 1.x and more recent ones were already available with pipeline version 2.x.

For the sake of simplicity, we call our algorithm MCDA (Modified *CoRoT* Detrend Algorithm). Our analysis is restricted to the CHR light curves, which were obtained using a dispersive device in front of the exoplanet channel detectors, which allowed us to discriminate transit events (quasi-achromatic) from stellar activity (strongly chromatic), among other characteristics (Auvergne 2003).

To do a confident assessment on how much we were able to reduce the dispersion on the data due to the presence of discontinuities, we performed the median of absolute deviations from the median (MAD) (Hoaglin, Mosteller & Tuckey 2000), which is a robust estimator of statistical dispersion. Using these estimates, we are able to assess qualitatively and quantitatively how well our detrending method performs when our results are compared to the raw measurements as well as to the detrending performed by the CDA.

In Fig. 1, we show an arbitrary light curve from the *CoRoT* data set with the presence of *jumps*. The original flux suffers as much from sudden displacements as from permanent deviations in the measurements. CDA turns out to be very effective in dealing with long trend deviations, but less so with short-term variations. It is probably the effect of a poor performance of the polynomial fit at the sharp changes in the vicinity of the *jumps*. On the other hand, MCDA was able to remove all the short- and long-term discontinuities as it can be seen in the bottom plot of the figure. The effectiveness of the technique, however, depends heavily on former assumptions as, for instance, the parameters adopted to perform the smoothing of the light curve (equation 1).

Of all runs available, LRA01 is especially interesting for its number of targets and also had been widely studied to determine the noise properties of the mission's data (Aigrain et al. 2009). So, to compare the methods and test their effectiveness, we show in Fig. 2 the MAD of the light curves after applying CDA versus the MAD of the raw data, and the same for MCDA. It is easy to see that MCDA was able to lower the MAD to almost 100 per cent of the 7470 CHR targets. In a few cases, it seems to have added a little noise to the light curves.

The use of a robust approach to assess the deviation's statistics allows MCDA to handle much better the global dispersion of the data, assuring to a higher degree that the chosen sets to be corrected indeed suffer from *jumps*. On the other hand, the lower performance of CDA comes from the way trends are filtered out, such as stellar

variability, in combination with the fact that discontinuities in the data deviates the probability distribution from normality, making standard statistical estimators less sensitive.

All the 24 runs studied showed a high improvement on the reduction of the dispersion similar to the run LRA01 in comparison to the original light curves. This shows that the technique is indeed contributing to enhance the detections in the light curves. These transits would not be prominent before due to the dominant signal of the jumps.

Since the method's procedure for correction is based on averaging the most affected colour with the least affected channel, a little increase on the occurrence of false positives could be expected, like signals that first appeared only in a single colour being imprinted now in other channels. This is however perfectly manageable since modelling of the candidates is preferably done with the raw light curves, where such false positives can be ruled out. On the other hand, the technique helps to lower the occurrence of false negatives, especially the cases where the transits are shallow and would be missed if the discontinuities were not properly handled in advance.

3 PHOTOMETRIC ANALYSIS

3.1 Transit detections

Transits are caused by the passage of an opaque body in front of a star in the line of sight of the observer. Planetary transits themselves usually have the shape of a box with soft edges caused by the limb darkening observed on the stellar disc. Rauer & Erikson (2007) and Winn (2010) explain in details the phenomenon of transits and the major misinterpretations which can originate from geometry or shape as well as from mimic situations such as background diluted binaries. Although this is a periodic event and there are many approaches to be employed in the frequency domain to detect these signals, box-shaped algorithms such as Box-fitting Least Squares (BLS) (Kovács, Zucker & Mazeh 2002) are more reliable to deal with low signal-to-noise ratio and also more efficient to perform transit searches as shown by Aigrain & Irwin (2004).

*CoRoT*Exo field has in total 176 492 light curves. From those, 65 655 are chromatic and 110 837 are monochromatic. We performed the detrending in the entire CHR data set. After applying MCDA, we did the search for periodic transits using the BLS algorithm. The output provided by the BLS algorithm is a periodogram. As defined by Kovács et al. (2002), each spike in the periodogram has a signal detection efficiency (SDE), which is dependent on the number of frequencies used to test for the presence of box-shaped signals. We established an SDE cut and ranked our first-generation candidates.

Many false positives can be ruled out at this stage. We tested for each candidate the difference in the depths of odd and even transits in the three channels independently. A visual inspection was carried out on each remaining pre-candidate checking for the occurrence of the transits in the three channels using the raw data. We also checked for the presence of shallow occultations and strong deep V-shaped transits, which are usually featured in binaries, due to the low radius ratio between the companions. To estimate the transit parameters in an optimal way, we analysed the singular spectrum of the variability present in the measurements as explained next.

Besides the already published *CoRoT* planets, we detected 45 still unpublished candidates within the depth limit of 2 per cent. Radial velocity measurements were publicly available in the ESO Science

Archive Facility for 11 of these cases, from which we chose three promising cases to present our findings.

3.2 Variability modelling

It is well known and expected that detrend techniques introduce distortions in the transit shapes compromising in some level the information on depth and duration of the event, and consequently the determination of transit parameters. To make the best use of the information, we performed a custom detrend in each candidate light curve with the aim of disentangling the transit signal from the variability present in the measurements.

The singular spectrum analysis (SSA) is a technique based on the division of a time series into its constituent parts of trends, periodicity and residual structures. It does not assume any parametric model and has been well employed in studies of non-trivial periodicities in Climate and Astronomy time series. To this end, it makes use of the decomposition of the original time series into sub data sets, building a multidimensional series from which the singular spectrum is produced – the spectral decomposition of the multidimensional series into its eigenvalues set (Elsner & Tsonis 1996; Ghil et al. 2002).

To isolate the variability present in the light curve, we modelled the undetrended light curve without the transits. To remove the transit signals properly, we did the following. First, corrections were performed when heavy discontinuities understood as systematics were found. The data was then re-sampled to a 512 s cadence and long trends were treated using a Savitzky–Golay filter (Savitzky & Golay 1964). A trapezoidal function was fitted over the time series folded on the candidate's period to derive the planetary parameters using the equations derived by Seager & Mallén-Ornelas (2003) and fitted with a Levenberg–Marquardt algorithm (Marquardt 2009). Finally, using the information on duration and epoch for each transit, they were located and removed from the corrected raw light curve and the gaps were interpolated using a polynomial function.

Using this corrected light curve without transits, we did the SSA of the time series and determined the significant components to reconstruct the signal. Doing so we are also able to some degree to remove the variability convolved with the transits and thus reduce the impact of the detrend in the transit parameters. The signal reconstruction from the SSA components was done using the eigenvalues that were above the noise level present in the light curve. To measure which eigenvalues could be distinguished from pure noise, we performed a 100 times Monte Carlo simulation shuffling the data for each light curve as employed before by Emilio et al. (2010). Fig. 3 shows the eigenvalues for 250 modes and the average eigenvalues found with the Monte Carlo simulation. Fig. 4 exhibits the signal reconstruction based on the eigenvalues calculated on the previous plot and the light curve detrended only with the transit signals.

4 SPECTROSCOPIC ANALYSIS

4.1 Measurements

From the list of host stars from the photometric data suspected or confirmed of having at least one exoplanet, spectroscopic data from the HARPS instrument were retrieved from the ESO Science Archive Facility (Retzlaff et al. 2014). HARPS is a fibre-fed cross dispersed spectrograph installed at the coudé west focus of the La Silla 3.6m telescope. Its main goal is the search for exoplanets using

Figure 3. Singular spectrum analysis of *CoRoT* ID 652345526. The solid line shows the eigenvalues of the 250 modes calculated using the corrected light curve. The dotted line represents the average eigenvalues after 100 Monte Carlo simulations shuffling the original data. The zoomed plot shows the significant components (stars) which are over the noise level components (triangles).

the radial velocity method with high accuracy (1 m s^{-1}) (Mayor et al. 2003). Table 1 lists the HARPS observations ranging from 2010 to 2013 for the host stars of interest which were obtained.

4.2 Stellar and planetary parameters

Spectra available from the ESO data bank are already reduced and wavelength calibrated, using the HARPS pipeline. Each spectrum was obtained using the high-accuracy mode with one fibre locked on the star and the other on the sky. The radial velocity was measured on each extracted spectrum by means of weighted cross-correlations with a G2 stellar mask. The uncertainty in RV measurements is mostly due to contributions by photon and read-out noise, wavelength calibration error and instrumental drift error (Fischer et al. 2016).

The spectroscopic analysis has been performed in two steps. First, spectra were analysed with the Spectroscopy Made Easy (SME) package (Valenti & Piskunov 1996) that derive accurate stellar parameters (temperature, surface gravity, [Fe/H], etc.). SME then produces a spectral synthesis of the star. Fig. 5 shows the spectral synthesis for *CoRoT*-32 (Table 2).

Table 1. HARPS spectroscopic data retrieved from the ESO Science Archive Facility for the host stars presented.

<i>CoRoT</i> ID	Number of spectra	Interval of observations
223977153	21	23/01/2010–05/02/2012
104848249	11	17/06/2012–28/09/2013
652345526	06	14/06/2012–09/07/2012

Afterwards, T_{eff} , $\log g$ and [Fe/H] were used as input for the Exofast algorithm (Eastman, Gaudi & Agol 2013). Exofast is an ensemble of routines which may be used to fit simultaneously exoplanetary photometric transits and radial velocity variations. The code makes a model of the planetary transit taking into account stellar and transit characteristics, giving the stellar and the planetary parameters as output, with the help of accurate mass and radius determination of stars by Torres, Andersen & Giménez (2010). We applied the Exofast algorithm to our three stars. The results are given on Tables 2 and 3.

As can be seen in Fig. 6, the results for the stellar parameters agree well with those expected for stars of similar masses and solar metallicity computed with the Geneva evolutionary track models (Schaller et al. 1992).

5 RESULTS

The contamination of eclipsing binaries diluted in the observed targets' flux is one major concern in the analysis of transit candidates and is commonly performed with follow-up photometry. Two of our targets (*CoRoT*-32 and *CoRoT* ID 104848249) were observed in two *CoRoT* runs with different masks. In this work, we also made use of the unprecedented data released by the *Gaia* mission (Gaia Collaboration et al. 2016a,b) as well as of the Sloan Digital Sky Survey Ninth Release – SDSS9 catalogue (Ahn et al. 2012). To rule out the sources that might be bright enough to mimic transit features we detailed all known stars present inside each object's observed mask and, taking the spectral response of the *CoRoT* satellite detectors as reference (Levacher 2006; Auvergne et al. 2009), estimated the total flux contribution of background sources. More details in the following subsections.

The measurements of the radial velocity of our targets where taken in a very irregular time spacing. This introduce false peaks in the power spectrum. We choose then to make the frequency analysis of the radial velocity measurements obtained by HARPS using the CLEANEST Algorithm (Foster 1996) and Period 04 (Lenz &

Figure 4. Singular spectrum reconstruction for the *CoRoT* ID 652345526 light curve. The five eigenvalues that are distinguishable from the noise level were used to reconstruct the variability of the light curve excluding the transits. The top image shows the original light curve and signal reconstruction represented by the solid line. At the bottom, the transits corrected for the variability.

Figure 5. Spectral synthesis results using the SME algorithm for *CoRoT*-32 done with a master spectrum integrated from the HARPS observed spectra. The blue line corresponds to the final synthesis.

Table 2. Stellar parameters based on calculations provided by the Exofast algorithm.

Parameter	Units	<i>CoRoT</i> -32	ID 104848249	ID 652345526
M_*	Mass ($M_\odot$)	$1.08^{+0.08}_{-0.07}$	$1.18^{+0.08}_{-0.07}$	1.41 ± 0.09
R_*	Radius ($R_\odot$)	$0.79^{+0.08}_{-0.09}$	1.22 ± 0.09	1.6 ± 0.1
L_*	Luminosity ($L_\odot$)	0.7 ± 0.2	2.24 ± 0.4	$4.75^{+0.9}_{-0.8}$
$\log(g_*)$	Surface gravity (cgs)	$4.67^{+0.11}_{-0.08}$	$4.21^{+0.07}_{-0.06}$	$4.13^{+0.05}_{-0.07}$
T_{eff}	Effective temperature (K)	5970 ± 100	6410 ± 100	6860 ± 100
[Fe/H]	Metallicity	0.0 ± 0.2	-0.2 ± 0.2	0.0 ± 0.2
$V \sin(i)^a$	Rotational velocity (km s^{-1})	3.2 ± 1.0	23 ± 1	21 ± 1
Spectral class		G0VI	F7V	F4V
Magnitude <i>G</i> band		14.108 ± 0.003^b	13.433 ± 0.001^c	12.870 ± 0.001^c

^aRotational velocities were calculated with the SME algorithm.

^bMagnitude obtained from SDSS9 catalogue (Ahn et al. 2012).

^cMagnitude obtained from *Gaia* catalogue (Gaia Collaboration et al. 2016a,b).

Breger 2005). CLEANEST is a time analysis technique to detect signals in time series with irregular time spacing. It uses statistics based from Lomb–Scargle modified periodogram (Scargle 1982) and the data-compensated discrete Fourier transform (Ferraz-Mello 1981). The power spectrum follows a chi-square distribution with an expected value of one and two degrees of freedom per frequency fitted. Period04 is a tool written in JAVA/C++ to find frequencies in astronomical time series containing gaps. It allows the calculation of the uncertainties of the fitted parameters by means of a Monte Carlo simulation. Both algorithms resulted in consistent results.

We also performed an F-test. This statistical test if the ratio of the sum of residuals squared decreases significantly more than the

relative change of the degrees of freedom from a simple model to a more complex one. The planetary system parameters were obtained using the Exofast algorithm Eastman et al. (2013) as explained in the previous section.

5.1 *CoRoT*-32b

This object, *CoRoT*-32, a faint star with coordinates $\alpha = 06:40:46.843$ and $\delta = +09:15:26.752$, during the mission. More details on the stellar parameters can be found in Table 2. The first measurements were taken in the SRa01 run during 2008 March. The second set was observed during the SRa05 campaign from 2011 November to 2012 January.

Table 3. Planetary parameters for the systems *CoRoT*-32b, *CoRoT* ID 104848249 and *CoRoT* ID 652345526. The outputs were obtained with the Exofast algorithm.

Parameter	Units	<i>CoRoT</i> -32b	104848249 cand.	652345526 cand.
Planetary parameters:				
P	Period (d)	$6.718\,37 \pm 0.000\,01$	$5.708\,52 \pm 0.000\,07$	$5.616\,18 \pm 0.000\,04$
a	Semimajor axis (au)	0.071 ± 0.001	0.066 ± 0.001	0.069 ± 0.002
M_P	Mass (M_J)	0.15 ± 0.10		
R_P	Radius (R_J)	$0.57^{+0.06}_{-0.05}$	0.65 ± 0.06	1.4 ± 0.1
ρ_P	Density (cgs)	$1.1^{+1.3}_{-0.8}$		
$\log(g_P)$	Surface gravity	$3.1^{+0.6}_{-0.3}$		
T_{eq}	Equilibrium temperature (K)	938^{+65}_{-52}	1330 ± 49	1560 ± 65
$\langle F \rangle$	Incident flux ($10^9 \text{ erg s}^{-1} \text{ cm}^{-2}$)	$0.18^{+0.05}_{-0.04}$	0.7 ± 0.1	1.4 ± 0.2
RV parameters:				
K	RV semi-amplitude (m s^{-1})	14 ± 10		
Primary transit parameters:				
T_C	Time of transit (BJD)	$2455\,901.811^{+0.002}_{-0.001}$	$2455\,299.387 \pm 0.001$	$2455\,662.5203 \pm 0.0004$
R_P/R_*	Radius of planet in stellar radii	0.054 ± 0.002	0.0552 ± 0.0009	0.095 ± 0.002
u_1	Linear limb-darkening coeff	0.35 ± 0.05	0.29 ± 0.05	0.22 ± 0.05
u_2	Quadratic limb-darkening coeff	0.28 ± 0.05	0.29 ± 0.05	0.30 ± 0.05
i	Inclination ($^\circ$)	89.0 ± 0.5	87.9 ± 0.2	$87.4^{+1.0}_{-0.7}$
b	Impact parameter	$0.4^{+0.1}_{-0.2}$	0.43 ± 0.02	$0.44^{+0.08}_{-0.14}$
δ	Transit depth	0.0029 ± 0.0002	0.0030 ± 0.0001	0.0091 ± 0.0003
τ	Ingress/egress duration (d)	0.006 ± 0.001	0.010 ± 0.001	0.020 ± 0.003
T_{14}	Total duration (d)	$0.104^{+0.009}_{-0.007}$	0.151 ± 0.009	0.187 ± 0.006
Secondary eclipse parameters:				
T_S	Time of eclipse (BJD)	$245\,5905.170^{+0.002}_{-0.001}$	$245\,5302.240 \pm 0.001$	$2455\,665.3284 \pm 0.0004$

Figure 6. Evolutionary tracks for selected solar mass stars using the Geneva stellar models (Schaller et al. 1992). Crosses represent the parameters of our selected stars derived using the Exofast code. [1] *CoRoT*-32; [2] *CoRoT* ID 104848249 and [3] *CoRoT* ID 652345526. See Table 2.

Previous studies had already been carried out for this target. Guenther et al. (2013) did high angular resolution measurements and infrared spectroscopy, but did not find any candidate companions very close to the star. Klagyivik et al. (2013) performed a variability survey in the *CoRoT* SRa01 field and classified the star as a Gamma Doradus variable with a period of 0.915 ± 0.005 d and amplitude 0.015 ± 0.008 mag. Therefore, none of the *CoRoT* photometric light curves have this period and our SME analysis of the HARPS spectra classify this star as G0VI.

To reinforce the analysis of background eclipsing binaries in addition to Guenther et al. (2013), we analysed the transits' depth in the three channels separately and compared the depths with all sources from the SDSS9 catalogue overlapping with the target's mask. We measured transits' depth of 0.0027 ± 0.0004 (red), 0.0029 ± 0.0007 (green) and 0.0028 ± 0.0009 (blue). Fig. 7(a) shows the contaminating sources present in the mask during the two runs. We converted the magnitudes into relative fluxes and used the transit depth as an estimate of what would be the apparent magnitude contamination limit. In this case, a 0.3 per cent flux variation sets a limit of 20.45 ± 0.08 mag. None of the sources present in the mask were bright enough to possibly mimic the observed transit. The total contamination as a function of the target star inside the mask is of 0.06 ± 0.02 per cent.

This star presents a strong activity visible in the light curves seen in both epochs (see Fig. 8). A modulation of ~ 11.4 d in the photometric data is best explained as due to stellar rotation. The same rotational frequency is found in radial velocity measurements. The $v \sin(i)$ found by the SME algorithm resulted in $3.2 \pm 1.0 \text{ km s}^{-1}$, with the estimated radius for this star, the rotation period (supposing $i = 90^\circ$) is 14 ± 6 d inside the 1σ error of the rotation photometric period found. Fig. 9 top panel shows the CLEANEST spectrum of the 21 radial velocity measurements of the target star. The rotational and the planetary periods are shown in vertical dashed lines and the significant levels are shown in dashed horizontal lines. Rotational period appeared as more than 95 per cent of significance in the CLEANEST power spectrum. The precision found in this frequency agrees with the photometric measurements within three significant figures. Another strong indicator is the anticorrelation observed when the bisector span was plotted against the radial velocity measurements (left-hand panel of Fig. 10).

We modelled this frequency up to its second harmonic and subtracted it from the radial velocity data as suggested by Boisse et al. (2011), taking into account the phase difference in each data set.

Figure 7. 2MASS fields (Skrutskie et al. 2006) detailing where each target was observed by the *CoRoT* mission. (a) *CoRoT*-32 (2MASS 06404684+0915267): the target is identified as source 1. A dashed line delineates the mask used during the SRa01 run while the plain line corresponds to the mask at the run SRa05. (b) *CoRoT* ID 104848249 (2MASS 18371179+0455427): star marked as source 3. The dashed mask corresponds to the run LRC05 and the plain mask to the run LRC06. (c) Field with *CoRoT* ID 652345526 (USNO-A2 0900-13043873) and has the star targeted as source 1. It was observed during the run LRC07. Each mask is divided in three regions corresponding to the three channels read out from the *CoRoT* frames and are indicated with their corresponding colours: red, green and blue. Magnitudes of contamination sources inside and neighbouring the masks are listed at the right side of each image and they were obtained from the SDSS9 (a) and *Gaia* (b and c) catalogues.

Figure 8. Light curves for *CoRoT*-32. Top: measurements of SRa01 campaign during 2008 March. Bottom: measurements of SRa05 campaign from 2011 November to 2012 January.

Figure 9. Top: CLEANEST spectrum of 21 measurements of radial velocity of *CoRoT*-32. The rotation and the planet period are shown in vertical dashed lines and the significant levels are shown in dashed horizontal lines. Rotational period appeared as more than 95 percent of significance in the CLEANEST power spectrum. Bottom: residual CLEANEST spectrum after subtracting the rotation signal resulted from our least-squares fit from the radial velocity measurements. The same period of ~ 6.7 d found in the photometric measurements appear as 98 percent of significance in the CLEANEST power spectrum.

Figure 10. Left: anticorrelation between bisector span and the radial velocity measurements of *CoRoT*-32 indicating the radial velocity measurements are affected by the stellar activity. Right: the same plot after subtracting from a stellar rotational model.

The first 8 radial measurements for this star is separated by 692 d from the last 13 measurements. The configuration of the star spots is expected to be different from each set, which will make the amplitude and phase different for the rotation. We notice that when making individual power spectrum for each of the two sets of data. The rotation period found in photometry measurements also have different phases. The best result came when we least-squares fit at once both data sets with the same rotation period but different phases and amplitudes and a unique phase and amplitude for the second period was found in the photometric data plus a constant.

Fig. 9 bottom panel shows the residual CLEANEST spectrum after subtracting the rotation signal resulted from our least-squares fit from the radial velocity measurements. The same period of ~ 6.7 d found in the photometric measurements appear as 98 percent of significance in the CLEANEST power spectrum. We also subtract the rotation signal from the bisector span plot to show the decrease of the anticorrelation (right-hand panel of Fig. 10).

Although the result obtained with the CLEANEST spectrum is statistically significant, we test if it is substantially significant analysing the spread on the weighted residuals given the hypothesis of the presence of a planet (see Beaugé, Ferraz-Mello & Michtchenko 2012). We ran 10^6 Monte Carlo realizations to compare the best weighted residual for two models: (a) only rotational

Figure 11. Top: best solution for the radial velocity measurements of *CoRoT*-32b after subtraction of the rotation period and its two first harmonics (see Table 3). In contrast to Table A1, the error bars account for the propagation of the uncertainties in the star's rotation model. Bottom: residuals after subtracting the planet's orbital model.

modulation due to stellar activity is present in the radial velocity data and (b) rotational modulation plus the gravitational pull of a planet. In this test, we used only the last set of the HARPS observations (13 measurements) to maximize the degrees of freedom ruling out the differences in rotational amplitude and phase between the two data sets.

The analysis took into account the time of the transits and the periods determined from photometry and we used only the fundamental rotational frequency. Before the test was performed, a study on orbital eccentricity was also done and, given the lack of data, it is equally likely to have $e = 0$ as values up to $e = 0.2$. Thus, we assume a more simple circular orbital model. The best solution found for the model *a* minimized the residuals (weighted root mean square) to 13.8 m s^{-1} . When we compare the results with *b*, we see a reduction to 9.4 m s^{-1} . The improvement observed lies close to 2σ which would give us an FAP not far from 4.5 per cent.

Therefore, to perform the analysis of the planet's signature in the radial velocity data (Table A1), we propagated in quadrature the uncertainties of the stellar rotation model. In Fig. 11, we show the radial velocity measurements and the best orbital solution for *CoRoT*-32b. A hot giant planet was found around the star. Table 3 shows the planetary parameters computed with the ExoFast algorithm. The semi-amplitude velocity of the planet found with realistic errors is $14 \pm 10 \text{ m s}^{-1}$ and corresponds to a body with $0.15 \pm 0.1 M_J$ and radius $0.57^{+0.06}_{-0.05} R_J$ with a period of $6.71837 \pm 0.00001 \text{ d}$ found both in photometric and spectroscopic data. The high precision of the period determination is due to the fact that the two data sets allowed the fitting of the transits within an interval of more than 200 orbits. Fig. 12 shows the folded light curve for *CoRoT*-32b. The planet orbits its host star which has a mass comparable to our Sun at a semimajor axis smaller than Mercury's orbit.

5.2 *CoRoT* ID 104848249

Fig. 13 shows the folded light curve for the *CoRoT* ID 104848249 observed during the campaigns LRC05 and LRC06. The star has coordinates $\alpha = 18:37:11.798$ and $\delta = +04:55:42.726$ and its apparent magnitude in the *R*-band is 13.7. The observational span

Figure 12. Folded light curve for *CoRoT*-32b.

Figure 13. The folded light curve for *CoRoT* 104848249.

in photometry is of 168.3 d with a short interval of a few days in between, from 2010 April to September.

The separate analysis of the transits in the three channels revealed depths of 0.0025 ± 0.0001 (red), 0.0025 ± 0.0002 (green) and 0.0028 ± 0.0002 (blue). Using the *Gaia* photometry information, we estimated the contamination limit for this transit depth in $19.74 \pm 0.04 \text{ mag}$ in the *G* band. Fig. 7(b) shows two contaminants inside the mask during the run LRC05 and one contaminant during the run LRC06. Both the cases are, in terms of brightness, close to the edge of the contamination limit as well as located at the edges of the blue channel. A comparison among the transits' depths and their uncertainties strongly suggests that they are actually a feature from the target star leaving little room for the case of a background contamination. The total contamination inside the mask as a function of the target star is estimated in 0.9 ± 0.4 per cent in the run LRC05 and 0.7 ± 0.3 per cent in the run LRC06.

Figure 14. CLEANEST spectrum of 11 measurements of radial velocity of CoRoT ID 104848249. The photometric period is shown in vertical dashed lines and the significant levels are shown in dashed horizontal lines.

Figure 15. The folded light curve for CoRoT 652345526.

The best-fitting parameters for the transit model are listed in Table 3. The candidate has a period of 5.70852 ± 0.00007 d and given the stellar parameters, we calculate a radius of $0.65 \pm 0.06 R_J$ and the semimajor axis of 0.066 ± 0.001 au.

11 radial velocity measurements were available at ESO Science Archive Facility (Table A2) covering 467.7 d. Fig. 14 shows the CLEANEST power spectrum of the radial velocity measurements for this star. The power spectrum is dominated by the window function. The photometric period of 5.7 d appear in the CLEANEST spectrum among a group of frequencies where the strongest peak have more than 80 percent of significance. The maximum semi-amplitude span found in the data is around 660 m s^{-1} and could indicate the presence of a companion up to $6 M_J$. The absence of anticorrelation between the bisector span and radial velocity suggests no perturbing stellar activity in the radial velocity data. More radial velocity measurements are needed to confirm beyond doubt the nature of the companion.

5.3 CoRoT ID 652345526

The photometry for this target was taken during the LRc07 run at coordinates $\alpha = 18:31:00.241$ and $\delta = +07:11:00.125$. It is a faint

star with apparent magnitude in the *R* band of 13.0 and 15 transits were observed during this time coverage.

The transit analysis in the three colours has shown to be very consistent. We measured a depth of 0.0086 ± 0.0006 in the red channel, 0.009 ± 0.001 in the green channel and 0.008 ± 0.001 in the blue channel. From the *Gaia* catalogue, we have a magnitude in the *G* band of 12.870 ± 0.001 , and an estimated contamination limit of 17.97 ± 0.04 mag. Fig. 7(c) shows two contaminants inside the observed mask with one case (object 2) where the measured magnitude overlaps the contamination limit. But the one magnitude level lower uncertainties found in the dispersion of the transit signal in the red channel antagonizes the fact that most of the signal comes from the blue channel. The amount of flux contamination inside the mask as a function of the target star is estimated in 1.0 ± 0.6 per cent.

The period found for this candidate is of 5.61618 ± 0.00004 d. It has $1.4 \pm 0.1 R_J$ and orbits the star at a distance of 0.069 ± 0.002 au. Fig. 15 shows the fold phased light curve and the residual from the adjusted model. More information about the transit and companion parameters are given in Table 3. Only six radial velocity measurements were available at the ESO Science Archive Facility covering 21.9 d for this star. We could make no further conclusions on the nature of the candidate. Moreover, we did not see strong indications of stellar activity given the stellar rotational velocity.

6 CONCLUSIONS

We presented in this work a modification of the CDA. The implementation using robust statistics decreased the systematic light-curve variations and improved the detection of exoplanets when comparing with the original algorithm. All CHR CoRoT light curves (a total of 65 655) were analysed in this work with our algorithm. All CoRoT known exoplanets in those light curves were found and we presented the analysis of three CoRoT photometric candidates. Spectroscopic measurements of the host star candidates were retrieved from the ESO Science Archive Facility public data base. We then derived the stellar parameters using the SME package and the Exofast algorithm. CoRoT ID 104848249 candidate has a period of 5.70852 ± 0.00007 and orbits a dwarf star with $1.22 \pm 0.09 R_{\odot}$. CoRoT ID 652345526 candidate has a period of 5.61618 ± 0.00004 d and orbits an F4V star with $1.6 \pm 0.1 R_{\odot}$. Both CoRoT ID 104848249 and CoRoT ID 652345526 need more radial velocity measurements to confirm the nature of these transits. A hot giant planet, CoRoT-32b, was found orbiting its very active parent star. With period of 6.71837 ± 0.00001 it is an exoplanet with mass of $0.15 \pm 0.10 M_J$ and $0.57^{+0.06}_{-0.05} R_J$. This star was observed in two CoRoT runs: SRa01 and SRa05.

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APPENDIX: RADIAL VELOCITY DATA

Table A1. *CoRoT*-32 radial velocities, their errors and bisector spans.

BJD	RV [km s ⁻¹]	Error [km s ⁻¹]	Bis [km s ⁻¹]
245 5219.590 65	16.913	0.006	0.002
245 5223.610 76	16.914	0.006	-0.035
245 5226.684 20	16.933	0.006	-0.023
245 5227.639 42	16.916	0.006	-0.035
245 5228.604 03	16.909	0.006	0.059
245 5229.659 77	16.926	0.007	0.036
245 5230.640 74	16.928	0.007	-0.011
245 5231.638 79	16.870	0.006	0.042
245 5923.726 85	16.955	0.004	-0.039
245 5924.741 79	16.957	0.004	0.006
245 5925.734 21	16.962	0.005	0.072
245 5926.692 39	16.958	0.005	0.014
245 5927.709 76	16.949	0.005	-0.055
245 5928.689 51	16.914	0.005	0.063
245 5929.700 52	16.890	0.005	0.039
245 5931.687 19	16.883	0.004	0.018
245 5932.688 97	16.886	0.004	0.027
245 5933.718 77	16.954	0.004	-0.008
245 5953.593 64	16.908	0.004	0.049
245 5960.563 29	16.978	0.005	0.001
245 5963.584 91	16.894	0.004	0.035

Table A2. *CoRoT* ID 104848249 radial velocities, their errors and bisector spans.

BJD	RV [km s ⁻¹]	Error [km s ⁻¹]	Bis [km s ⁻¹]
245 6096.790 74	3.062	0.004	-0.514
245 6099.764 91	3.109	0.005	-4.237
245 6117.562 91	3.036	0.004	-0.389
245 6119.635 06	3.551	0.005	-0.160
245 6151.650 12	2.991	0.005	-0.443
245 6154.595 11	3.652	0.005	-0.173
245 6158.473 38	3.131	0.005	-0.010
245 6160.562 14	3.659	0.006	-1.077
245 6509.642 82	3.271	0.005	1.163
245 6539.531 56	3.357	0.005	26.245
245 6564.499 67	3.387	0.004	-1.155

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