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PRE-DISCOVERY OBSERVATIONS OF CoRoT-1b AND CoRoT-2b WITH THE BEST SURVEY

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ABSTRACT

The Berlin Exoplanet Search Telescope (BEST) wide-angle telescope installed at the Observatoire de Haute-Provence and operated in remote control from Berlin by the Institut für Planetenforschung, DLR, has observed the CoRoT target fields prior to the mission. The resulting archive of stellar photometric light curves is used to search for deep transit events announced during CoRoT’s alarm mode to aid in fast photometric confirmation of these events. The “initial run” field of CoRoT (IRa01) was observed with BEST in 2006 November and December for 12 nights. The first “long run” field (LRc01) was observed from 2005 June to September for 35 nights. After standard CCD data reduction, aperture photometry has been performed using the ISIS image subtraction method. About 30,000 light curves were obtained in each field. Transits of the first detected planets by the CoRoT mission, CoRoT-1b and CoRoT-2b, were found in archived data of the BEST survey and their light curves are presented here. Such detections provide useful information at the early stage of the organization of follow-up observations of satellite alarm-mode planet candidates. In addition, no period change was found over ~4 years between the first BEST observation and last available transit observations.

Key words: planets and satellites: individual (CoRoT-1b, CoRoT-2b) – techniques: photometric

Online-only material: color figure

1. INTRODUCTION

The Berlin Exoplanet Search Telescope (BEST) is a 19.5 cm aperture wide-angle telescope dedicated to time-series photometric observations (Rauer et al. 2004). The main purpose of the instrument is to provide ground-based support to the CoRoT space mission (CNES; Baglin et al. 2006). The mission target fields are observed at least one year prior to the observations of the spacecraft. Therefore, planetary transit candidates found by CoRoT at bright stars can be searched for quickly in the BEST archive to confirm the transit event and to check the ephemeris. In addition, BEST data sets are used to search for new variable stars in the CoRoT target fields which are input to the additional science program, e.g., eclipsing binary stars (Karoff et al. 2007; Kabath et al. 2007, 2008). Furthermore, information on variable stars nearby CoRoT transit candidates can be used to help disentangling crowding problems during the CoRoT light-curve analysis.

The transit signals of the first two planets detected by CoRoT (CoRoT-1b and CoRoT-2b; Barge et al. 2008; Alonso et al. 2008), were found using the “alarm detection mode” of the mission, during ongoing observations of the respective target fields. Since both planets orbit relatively bright stars, we searched for signatures of the transit candidates in our BEST data archive. Partial transit events of the planets were recorded by BEST in 2006 December and summer 2005 during observations of the CoRoT “initial run” and first “long run” fields. In the following, we describe these pre-discovery observations of CoRoT-1b and CoRoT-2b.

2. THE BEST SYSTEM

2.1. Telescope and Instrumentation

The observations were performed with the BEST system (Rauer et al. 2004). The BEST Telescope is a commercial flat-field telescope with 19.5 cm aperture and f/2.7 focal ratio and is mounted on a German equatorial mount. The system uses an air cooled Apogee-10 CCD camera with 2048 × 2048 pixels and a pixel scale of 5.5 arcsec/pixel−1, resulting in a 3.1 × 3.1 deg2 field of view (FOV). The readout time of the CCD is 9 s and the saturation level is reached with 16,384 ADU. In order to detect as many photons as possible no filters are used. Guiding of the telescope is performed by a 9 cm aperture telescope equipped with an ST-4 CCD camera.

The BEST system has been located at the Observatoire de Haute-Provence (OHP), France, since 2004. During the commissioning phase of the BEST telescope for the OHP site, the system was upgraded to allow remote control of all its components as well as a system and environment monitoring. In autumn 2006, the first observations in remote control mode were performed by an observer at DLR in Berlin. Since then, the system is controlled from Berlin with occasional technical service visits at OHP. The remote observer starts the system at the beginning of the night and operates until the target field is acquired. Then, automatic exposure sequences are taken throughout the night. The DLR staff cooperates with local Berlin amateur astronomers who participate in the remote observations.

Observations are obtained for typically 30,000 stars in a target field. The reduced stellar light curves are archived for subsequent analysis.
2.2. Data Center and Archiving

In order to process the observational data acquired with the BEST telescope efficiently, a dedicated data processing center consisting of a computer cluster system was installed at DLR during spring 2006. The data processing center consists of 18 calculation nodes and 3 Tb disk space in total.

The BEST stellar light-curves database contains stellar coordinates, time of observation, magnitude, and magnitude error of the individual measurements for each detected star within the BEST fields. To allow a first estimate of stellar variability in the light curves, a variability index calculated according to Zhang et al. (2003) has been included. The content of the database is available to the scientific community upon request.

3. OBSERVATIONS

In the following, we describe the data obtained on the CoRoT IRA01 and LRc01 stellar fields which were used to check the transit candidates of the later confirmed planets CoRoT-1b and CoRoT-2b.

3.1. General Observing Modes

The CCD is cooled to its operational temperature around 20 °C below outdoor temperature. Due to the location in Haute-Provence, the outdoor temperature changed over the seasons with extreme values between −10 °C and +20 °C. However, variations during the observations were mostly limited to a couple of degrees once stabilized during the astronomical night. Calibration bias frames and dome flat fields are acquired at the beginning of each night.

The general scientific observing sequence consists of a series of 40 s exposures followed by a 240 s exposure. Dark frame images are taken every 25 minutes with the same exposure time as the science images. This fully automated sequence takes about 30 minutes. The resulting duty cycle for the scientific images on an average is around 50%–60%. The dark and bias frames acquired within the observing session are used to monitor the performance of the CCD over the night. At the end of the observing runs, additional bias and dark frames are taken for calibration purposes.

3.2. BEST Data Sets of the CoRoT IRA01 and LRc01

The IRA01 field was observed in 12 nights spread over a period of 40 days from 2006 November 11 to December 21 (Kabath et al. 2007). The LRc01 field was observed from 2005 June 6 until September 7 in 35 nights spread over 89 days (Karoff et al. 2007). No observations were performed for six days around the full Moon. Additional data gaps resulted from bad weather conditions at OHP.

The observed CoRoT IRA01 field is located at R.A. = 06h57m18s and decl. = −01°42′00″ (J2000.0) (Michel et al. 2006). The BEST field of view (FOV) covered the CoRoT exoplanetary field only to avoid the bright stars in the CoRoT asteroseismology field. The BEST FOV, therefore, was centered at R.A. = 06h46m24s and decl. = −01°54′00″ (J2000.0).

The CoRoT LRc01 field is located at R.A. = 19h23m33s and decl. = +00°27′36″ (Michel et al. 2006). Again, the BEST FOV was offset to avoid the bright asteroseismology target stars and was centered at R.A. = 19h00m00s and decl. = +00°01′55″.

Since the CoRoT fields are located near the celestial equator, they can be observed only at relatively low altitudes (< 50°) from OHP. Therefore, the BEST data set had to be obtained at relatively high air mass. Typically observation arcs ranged between 3 and 6 hr per night.

In this paper, we analyze the images acquired with 240 s exposure time since they provide an overlap with the CoRoT magnitude range with sufficient photometric precision. The data sets contain in total 300 frames for the IRA01 field and 727 frames for the LRc01 field. The magnitude range of the detected stars in the BEST fields (about 30,000) is 10–18 mag and thus overlaps with the CoRoT magnitude range (12–16 mag). Typically, during a good photometric night, BEST acquires light curves with a precision ≤1% for 3000–4000 stars in the range 10–13 mag.

4. BEST DATA REDUCTION PIPELINE

The BEST data reduction pipeline includes the basic CCD imaging reduction steps, such as dark current and bias subtraction as well as flat-fielding, which have been performed by computing the related master frames for each night (Rauer et al. 2004; Voss 2006). For the photometric data reduction, we used the ISIS image subtraction method. A detailed description of the ISIS method can be found in Alard (2000).

In a first step, the stellar coordinates in every image are interpolated with respect to a single chosen reference frame from the middle of the observation run. For this purpose, the matching routine interp from the ISIS package (Alard 2000) was used. In this way, slight translations are well corrected and a coordinate template common to all images is created.

In a second step, the ISIS image subtraction method is applied to remove background contaminants to the stellar light. This is done by subtracting a reference frame from all the scientific frames thereby leaving only the remaining variability of each star as the final product. In this process, all frames have to match to the same seeing. The used reference frame is created from typically the 10 best seeing images obtained during the whole observation campaign. This reference frame is thereafter subtracted from all other images, such that the stellar point-spread function (PSF) on the reference frame is convolved with the corresponding stellar PSFs on the scientific images to best match the stellar PSFs in each individual frame. To obtain the flux variation of each star as a function of time, aperture photometry is applied on the reference frame and on all convolved and subtracted frames. The magnitude of each star was determined by aperture photometry in the reference frame. The magnitude at each time step was then determined by adding the deviations from the reference which were determined using the same aperture in the individual difference frames. The implementation of the BEST data pipeline is described in Karoff et al. (2007). Discussions on the obtained photometric quality for the CoRoT fields IRA01 and LRc01 can be found in Kabath et al. (2007) and Karoff et al. (2007). A local extinction correction is performed within the ISIS package that significantly reduces the influence of differential extinction present due to the large FOV. We use a fixed aperture of 7 pixels to match the FWHM range between 1 and 3 pixels of the analyzed stars as discussed in Karoff et al. (2007).

In the last step the (x, y) coordinates of the CCD frames are transformed into right ascension and declination. For such astrometric transformation, we compared the 300 brightest stars in the BEST data set with the USNO-A2.0 catalog using the MATCH routine (Valdes et al. 1995) to determine the transformation parameters. Thereafter, the transformation of the full BEST data set was performed and the corresponding
CoRoT-1b and our BEST data archive, based on the determined transit epochs. We therefore searched for signatures of the transit candidates in the magnitude range covered by BEST. Furthermore, their transits are strong signals of more than 2% and 3% depths, respectively. The planets orbit relatively bright stars ($V = 12.57$ mag for CoRoT-2b) but within the magnitude range covered by BEST. As a consequence, using the normal data pipeline with a photometric aperture of 7 pixels, resulted in a diluted signal of CoRoT-1b order. Nevertheless, the transit signature can be seen in the data. For comparison, another star of similar magnitude in the vicinity is also presented in the figure.

5. RESULTS

5.1. Photometric Pre-discovery Observations of CoRoT-1b and CoRoT-2b

The two planets CoRoT-1b and CoRoT-2b were discovered by the CoRoT space mission in the “alarm mode” during observations of its “initial run” (IRa01) and the first “long run” (LRc01) fields (Barge et al. 2008; Alonso et al. 2008). The planets orbit relatively bright stars ($V = 13.6$ mag for CoRoT-1b and $V = 12.57$ mag for CoRoT-2b) but within the magnitude range covered by BEST. Furthermore, their transits are strong signals of more than 2% and 3% depths, respectively. We therefore searched for signatures of the transit candidates in our BEST data archive, based on the determined transit epochs from the CoRoT alarm-mode operations. The star and planet parameters for CoRoT-1b and CoRoT-2b are given in Table 1.

The BEST archive data sets of the respective fields include 12 nights for the IRa01 and 35 nights for the LRc01 field. Figure 1 shows the target stars and their near vicinity. CoRoT-1b is located in a very crowded part of the CoRoT field. As a consequence, using the normal data pipeline with a photometric aperture of 7 pixels, resulted in a diluted signal where a neighboring star contributed to the total flux within the aperture. To minimize this effect, manual photometry with an aperture size of 5 pixels was performed in order to obtain optimum photometric accuracy. In all other aspects, the reduction for CoRoT-1b was performed as outlined in the previous section. CoRoT-2b was processed using the standard BEST pipeline.

Due to the restricted data set, only one partial transit event of CoRoT-1b was covered by BEST observations. Figure 2 shows the light curve obtained for CoRoT-1b on 2006 December 10. Only the egress of the transit event could be covered at the beginning of the night. The data set is severely affected by noise due to the weather situation. In addition, the star is located at the fainter end of the BEST magnitude range for signals of the CoRoT-1b order. Nevertheless, the transit signature can be seen in the data. For comparison, another star of similar magnitude in the vicinity is also presented in the figure.

Figure 3 shows the composite light curve obtained on CoRoT-2b by BEST. In total, three transit events could be covered in the observing period from 2005 June to September. Again, the data quality varies from night to night due to the weather situation, and on two nights only partial transits could be obtained. However, an almost complete transit signal is detected on 2005 July 14. Phase folding of the light curves from the individual nights has been done using the epochs and orbital period determined from the CoRoT data (see Table 1). For comparison, another star is also presented in the figure. A good agreement was found in orbital period and transit shape between the events detected by BEST and the more detailed CoRoT observations.

In both cases, the pre-discovery observations of CoRoT-1b and CoRoT-2b with the BEST survey were used during CoRoT follow-up observations to refine early ephemeris and optimize the effort to confirm their planetary nature (Barge et al. 2008; Alonso et al. 2008). The light-curve data used in this paper are given in Tables 2 and 3.
5.2. Detailed Analysis of a CoRoT-1b Transiting Event

In our data set, we found a partial transit event of CoRoT-1b (Figure 2). The data points cover the egress event. This observation of a transit was obtained 60 days before the discovery observations by the CoRoT satellite. We therefore tried to constrain the midcenter time to obtain an additional point for an O–C analysis.

For this purpose, we fixed the stellar, planetary, and orbital parameters at values given in Barge et al. (2008). The only free parameter was the midtime of the transit. The cycle number at the time of observations was −53, and therefore the predicted time of the transit is HJD 2 454 079.4785. We scanned the region around this predicted time (±4 hr) with a step size of 0.5 s to find the best agreement between the model and the observed light curves. Instead of the original light curve we used a smoothed light curve, applying a two-point moving average in order to increase the signal-to-noise ratio. The resulting midcenter time of the transit was found to be $T_{\text{mid}}(\text{HJD}) = 2454079.4673 \pm 0.0088$. The $O - C$ value corresponds to $O - C = -0.0112 \pm 0.0088$ days. The $O - C$ value determined from this partial light curve is zero within the 3σ error bars, and we conclude that our observation is in agreement with the ephemeris of Barge et al. (2008).

5.3. Detailed Analysis of CoRoT-2b Transiting Events

Our transit observations of CoRoT-2b were obtained two years prior the discovery, therefore we can extend its $O - C$ diagram which is the base of the period studies.
fitting the light curves of individual transit events, but there can be at least three approaches: (1) fitting every parameters, (2) fitting every parameters except the period, or (3) fitting only the midtransit times. The first method—fitting all the parameters—could not be applied here because we did not have enough data points to determine the epoch and period only from our observations. The second and third methods (fitting everything except period which is fixed) were tried.

We chose the quadratic limb-darkened model of Mandel & Agol (2002) who gave analytic expressions for the light loss of the system. In this model, the planet is dark without observable radiation while the stellar disk is limb-darkened and both objects are spherical. This model has seven free parameters: orbital inclination, radius of the planet and the size of the semimajor axis (both of them is expressed in stellar radius unit), two limb-darkening coefficients, the period, and the epoch.

To find the best agreement between the model and the data, a Markov Chain Monte Carlo method complemented with the Metropolitan-Hastings algorithm (see, e.g., Croll 2006) was used.

In Figure 3, we show the results of both fitting approaches. The "long-dashed" line represents the model for the CoRoT data be at least three approaches: (1) fitting every parameters, (2) fitting every parameters except the period, or (3) fitting only the midtransit times. The first method—fitting all the parameters—could not be applied here because we did not have enough data points to determine the epoch and period only from our observations. The second and third methods (fitting everything except period which is fixed) were tried.

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To find the best agreement between the model and the data, a Markov Chain Monte Carlo method complemented with the Metropolitan-Hastings algorithm (see, e.g., Croll 2006) was used.

In Figure 3, we show the results of both fitting approaches. The "long-dashed" line represents the model for the CoRoT data
from Alonso et al. (2008), only the midtransit time was adjusted. The “long–short-dashed line” represents the fitted model to the BEST data where only the period was fixed at the value given in Alonso et al. (2008). In the descending and ascending branch of the transit, the agreement is perfect but at the bottom part of the transit there is a small deviation. This deviation is caused by the different values of limb-darkening coefficients. These coefficients were fitted in Alonso et al. (2008) and in our case. The CoRoT and BEST light curves have a different number of data points and different accuracies and hence we cannot determine these coefficients from the BEST light curves with such high accuracy as Alonso et al. (2008). However, the semimajor axis and planet radius are in reasonable good agreement and the inclination differs by only 2.5. This good agreement in the planet to star radii ratio and semimajor axis is due to the fact that the light curves at this photometric accuracy level are not too sensitive to the limb darkening (Southworth 2008). This comparison illustrates that the data from ground-based surveys can be used for a realistic estimation of the planet parameters of detected exoplanets.

5.4. $O−C$ Analysis of CoRoT-2b

Our observations of CoRoT-2b were obtained almost two years prior to the CoRoT data. We, therefore, investigated whether a significant $O−C$ deviation could be detected in comparison to the ephemerides given in Alonso et al. (2008). With these three new transits in total 15 observed transit timing data points are available for CoRoT-2b. The sources of the other 12 points are one from Alonso et al. (2008), one from Vereš et al. (2009), and ten from the AXA working group (AXA: Amateur eXoplanets Archive, see: http://brucegary.net/AXA/x.htm).

To determine the midtime of the observed transits, we fixed the model parameters at the values given in Alonso et al. (2008) with the exception of the midtime of the CoRoT transit. Only this parameter was adjusted to obtain an optimized fit of all observed transiting events. The corresponding $O−C$ values can be found in Table 4 and in graphical form in Figure 4.

The interpretation of this diagram is difficult because of two reasons. First, there is a lack of available observational data, which means that the $O−C$ is not well covered. Second, the precision of the published minima times allows only the study of large period changes.

The deviation of all $O−C$ values yielded $\chi^2 = 440$ when using the ephemeris of Alonso et al. (2008). A simple linear fit of the $O−C$ diagram yielded the following ephemeris:

$$T_{\text{min}}(\text{HJD}) = 2454237.5357(16) + 1.7429861(58) \times E.$$  (1)

With this ephemeris, we reached $\chi^2 = 315$, and some improvement in the $O−C$ deviations. The new period value (1.742961 days) is shorter than the one in Alonso et al. (2008) by 0.9 ± 0.5 s. We conclude that there is no observable sign of period change in the available CoRoT-2b transit timing data. The lack of observed period change is in agreement with the results of Alonso et al. (2009). They analyzed the transit times in the CoRoT data and found no clear sign of periodic period change which would have amplitudes larger than 10 s. However, Alonso et al. (2009) did not publish their individual $O−C$ data thereby preventing a direct comparison with our result. Vereš et al. (2009) did also not find any sign of period variation on a shorter baseline of observations.

6. SUMMARY

We present pre-discovery observations of the first two planets detected by the CoRoT space mission, CoRoT-1b and CoRoT-2b. The transit events were detected in the BEST data archive, based on the epochs determined from the CoRoT data (Barge et al. 2008; Alonso et al. 2008). Although the observational duty cycle was severely affected by bad weather conditions, partial transits of both planets were detected by BEST. A transit of CoRoT-1b was observed on 2006 December 10. Transits of CoRoT-2b were observed on 2005 July 14, 2005 July 28, and 2005 August 4. No significant $O−C$ deviation in comparison to the ephemerides of Alonso et al. (2008) was found.

When planetary candidates are first announced from the CoRoT alarm mode, their ephemeris can be based on few transit events only. At this point, confirmation from ground-based observations taken one or more years prior to the spacecraft observations aids in checking the ephemeris quickly. In addition, these observations confirm the transit on the prime target and help identifying close possibly contaminating variable stars. We will continue to use the BEST data archive for this purpose in future to support the planet search in particular during the alarm mode of CoRoT, when primarily deep transits around bright stars are detected which overlap with the detection range of BEST.

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REFERENCES

Alard, C. 2000, A&AS, 144, 363
Alonso, R., Aigrain, S., Pont, F., Mazeh, T., & The CoRoT Exoplanet Science Team. 2009, in IAU Symp. 253, Transiting Planets, ed. F. Pont, D. Sasselov, & M. Holman (Dordrecht: Kluwer), 91
Alonso, R., et al. 2008, A&A, 482, L21
Baglin, A., et al. 2006, in ESA Special Publication 1306, ed. M. Fridlund et al., 33
Barge, P., et al. 2008, A&A, 482, L17
Brown, T. M., Charbonneau, D., Gilliland, R. L., Noyes, R. W., & Burrows, A. 2001, ApJ, 552, 699
Croll, B. 2006, PASP, 118, 1351
Kabath, P., et al. 2007, AJ, 134, 1560
Kabath, P., et al. 2008, AJ, 136, 654
Karoff, C., et al. 2007, AJ, 134, 766
Mandel, K., & Agol, E. 2002, ApJ, 580, 171
Michel, E., et al. 2006, in ESA Special Publication 1306, ed. M. Fridlund et al., 39
Rauer, H., Eislöffel, J., Erikson, A., Guenther, E., Hatzes, A. P., Michaelis, H., & Voss, H. 2004, PASP, 116, 38
Southworth, J. 2008, MNRAS, 386, 1644
Tamuz, O., Mazeh, T., & Zucker, S. 2005, MNRAS, 356, 1466
Valdes, F. G., Campusano, L. E., Velasquez, J. D., & Stetson, P. B. 1995, PASP, 107, 1119
Vereš, P., Budaj, J., Világi, J., Galád, A., & Kornoš, L. 2009, Contrib. Astron. Obs. Skalnate Pleso, 39, 34
Voss, H. 2006, PhD thesis, TU Berlin
Zhang, X.-B., Deng, L.-C., Xin, Y., & Zhou, X. 2003, Chin. J. Astron. Astrophys., 3, 151