A Method to Identify and Characterize Binary Candidates—A Study of CoRoT Data

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ABSTRACT. The analysis of the CoRoT space mission data was performed aiming to test a method that selects, among the several light curves observed, the transiting systems that likely host a low-mass star orbiting the main target. The method identifies stellar companions by fitting a model to the observed transits. Applying this model, which uses equations such as Kepler’s third law and an empirical mass-radius relation, it is possible to estimate the mass and radius of the primary and secondary objects, as well as the semimajor axis and inclination angle of the orbit. We focus on how the method can be used in the characterization of transiting systems having a low-mass stellar companion with no need to be monitored with radial-velocity measurements or ground-based photometric observations. The model, which provides a good estimate of the system parameters, is also useful as a complementary approach to select possible planetary candidates. A list of confirmed binaries is presented, together with our estimate of their parameters. The characterization of the first 12 detected CoRoT exoplanetary systems was also performed and agrees very well with the results of their respective announcement articles. The comparison with confirmed systems validates our method, especially when the radius of the secondary companion is smaller than $1.5 \, R_{\text{Jup}}$, in the case of planets, or larger than $2 \, R_{\text{Jup}}$, in the case of low-mass stars. Intermediate situations are not conclusive.

Online material: color figures

1. INTRODUCTION

The analysis of transiting systems based on light-curve modeling combined with ground-based follow-up by means of radial-velocity measurements have shown their exceptional importance in the characterization of extrasolar systems. Together, they provide the determination of several physical and orbital parameters that cannot normally be obtained for nontransiting systems, such as the mass and radius of the secondary companion and, thus, its density. The possibility of a detailed study of extrasolar transiting light curves in a large number of targets has been considerably improved by recent photometric space missions, such as Convection Rotation and planetary Transits (CoRoT; Baglin et al. 2006) and Kepler (Borucki et al. 2010).

At the time of this writing, since its launch, the CoRoT space telescope has collected the light curves of more than 100,000 stars through 13 observational runs. This huge number of stars is a strong motivation to develop tools to efficiently treat the released data, especially considering that the data first need to be cleaned from long-term variations, short-term oscillations, outliers, discontinuities, and more. Regarding the characterization of extrasolar systems, an extra challenge is to distinguish transits caused by planetary companions from those related to the presence of a low-mass star in a binary system, particularly given the time-consuming ground-based observations that are normally used as a complementary approach.

Carpano et al. (2009) published their results concerning the analysis of CoRoT light curves observed during the initial run of the mission, named IRa01, in which they presented a list of 50 planetary candidates, together with a list of 145 eclipsing binary candidates. Moutou et al. (2009) complemented the work of Carpano et al. (2009) with additional follow-up observations, also in the context of the initial run. In two articles published by Deeg et al. (2009) and Cabrera et al. (2009), the authors presented a list of targets for which ground-based follow-up was...
conducted, providing a complementary approach in the classification of the candidates. The lists released by these articles are the result of a huge effort of several working groups and show how difficult it is to characterize systems, planetary candidates or not, among thousands of targets.

In the work of Silva & Cruz (2006), the authors proposed a method based on the fit of light curves with transits that can be used in the characterization of transiting systems. This method provides the determination of some parameters of the system, such as the orbital inclination angle, the semimajor axis, and the mass and radius of the primary and secondary objects. In the present work we have used an updated version of the same method, applied to a list of transiting light curves from publicly available runs of the CoRoT mission. The purpose of our analysis is to show that the method is useful to identify transits most likely caused by a binary configuration, without making use of any time-consuming effort to conduct ground-based follow-up, such as radial-velocity measurements or photometric observations.

Silva & Cruz (2006) also tested their model applied to the transiting exoplanetary systems known at that time, and their results are in good agreement with the published parameters. Therefore, we also analyzed the first confirmed CoRoT planetary systems, from CoRoT-1 through 12, comparing our estimates with those in their respective announcement articles.

Section 2 presents the data reduction, showing the corrections needed to apply to the light curves (in the format delivered to the scientific community) before modeling the transit shape. Next, § 3 describes the method and its usefulness in the classification of binary system candidates. In § 4, the results are presented and discussed, which includes our parameter estimate for a list of binary systems first identified by other works, as well as the characterization of confirmed CoRoT exoplanetary systems. Finally, § 5 presents the final remarks and conclusions.

2. SAMPLE DATA AND REDUCTION

The light curves analyzed using our method are part of the three-color band data from publicly available runs observed by the CoRoT mission (a few cases of monochromatic light curves were also included). Before doing any kind of fit to model the observed transits, the light curves have to be cleaned from any systematic noise that may still remain in the data delivered to the scientific community, for which the format is called the N2 level (Baudin et al. 2006). The systematic noise normally seen is related to: 1) discontinuities produced by hot pixels; 2) outliers, whose sources are diverse; and 3) short-term oscillations related to the CoRoT orbital frequency (103 minutes) and its harmonics. For details on the CoRoT satellite and its orbit, see, e.g., Boisnard & Auvergne (2006) and Auvergne et al. (2009). In addition to the systematic noise, short-term oscillations, intrinsic to some types of stars, were also observed in some light curves and were removed.

We developed a code to correct the light curves from discontinuities and outliers. The code computes the first derivative of the data points in order to locate the discontinuities, then it fits polynomial functions to points between them, and the light curve is finally normalized according to such functions. When searching for the best fit, the code does not consider 1) data points located outside twice \( \sigma \), for which the value is estimated in a specific portion of the light curve, and 2) data points located where transits happen. We note that a visual inspection is always conducted to avoid any abrupt behavior of the fitted function, especially close to transit times. Figure 1 shows an example of this polynomial function fit.

Short-term oscillations may also affect the search for the model that best fits the observed transits. Figure 2 shows an example of transiting light curve when this kind of oscillation is present. The same object is shown in Figure 3 after being corrected from the most prominent harmonics. Oscillations due to the intrinsic variability of some stars were also properly removed when needed.

3. LIGHT-CURVE FIT

The method developed by Silva & Cruz (2006) was used here to search for the best model parameters that fit the observed
light-curve transits. The model considers an opaque disk that simulates the secondary object passing across the stellar disk. We assumed a quadratic function to describe the limb-darkening of the disk of the primary object, which is based on the star HD 209458 ($u_1 = 0.2925$ and $u_2 = 0.3475$, from Brown et al. 2001). An exception is the system 0100773735 (LRc01, Fig. 3), for which $u_1$ and $u_2$ were assumed to be half of those of the star HD 209458. In the case in which the secondary companion is a low-mass star, it will not be an opaque disk. However, this will not considerably change the results, since its flux contribution is small compared with the main star (a 0.3 $M_{\odot}$ star orbiting a solar-type star contributes less than 2% to the total flux). Cases in which the secondary is as bright as the primary were not selected in our analysis, given the large transit depth that would be observed in the light curve.

The orbital period ($P$) of the companion is a known parameter, obtained directly from the light curve, whereas the following three variables are the result of the best fit: the radii ratio between secondary and primary objects ($R_p = R_2/R_1$), the semimajor axis of the secondary orbit in units of the primary radius ($a_p = a/R_1$), and the orbital inclination angle ($i$). The search for the best fit is conducted with the AMOEBA routine (Press et al. 1992), which performs a multidimensional $\chi^2$ minimization of the function $f (R_p, a_p, \text{ and } i)$ describing the transit profile.

The first set of parameters normally used as input are $R_p = 0.1$, $i = 85^\circ$, and $a_p = a/R_1$, calculated according to Kepler’s third law (eq. [3]) for $M_1 + M_2 \sim 1 M_{\odot}$ and $R_1 \sim 1 R_{\odot}$. In order to avoid premature convergences on local minimums and to explore the entire parameter space, the best solution is found after running the routine several times, replacing the input parameters by new values within a chosen range (e.g., $\Delta R_p = \pm 0.05$, $\Delta a_p = \pm 3.0 R_1$, and $\Delta i = \pm 5^\circ$). Throughout the execution of the process, a visual inspection of the fit is carried out after each possible solution is achieved. Figure 4 shows an example of $\chi^2$ minimization for the system 0100773735 (LRc01).

### 3.1. Estimate of Mass and Radius

The method used to estimate the mass and radius of the primary and secondary companion was updated using new mass-radius relations based on more recent discoveries, especially the one fitted to known exoplanets (systems presently listed in the Extrasolar Planets Encyclopaedia’ were used). These relations are

$$R = AM_B,$$  \hspace{1cm} (1)

$$R = CM + D,$$  \hspace{1cm} (2)

where $A = 0.013938$, $B = 3.867270$, $C = 0.410162$, and $D = 0.065934$. The function given by equation (1) was fitted to stars, whereas equation (2) represents a function fitted to known exoplanets and the planets of the solar system. Both functions are plotted in Figure 5. Exoplanets having a radius greater than $1 R_{\text{Jup}}$ or mass greater than $2 M_{\text{Jup}}$ and low-mass objects having a radius less than $2 R_{\text{Jup}}$ were not used in the search for the best fit. These objects belong to an ambiguous region of the mass-radius diagram, in which a change in mass does not necessarily imply a change in radius.

After applying our method to the observed transits, we are able to estimate the mass and radius of both the primary ($M_1$ and $R_1$) and secondary ($M_2$ and $R_2$) objects and the orbital semimajor axis $a$ (given in astronomical units) using the following relations:

$$a^3 = \frac{GP^2}{4\pi^2} (M_1 + M_2),$$  \hspace{1cm} (3)

$$R_p = \frac{R_2}{R_1} ,$$  \hspace{1cm} (4)

$$a_p = \frac{a}{R_1} ,$$  \hspace{1cm} (5)

$$R_1 = AM_{1B} ,$$  \hspace{1cm} (6)

$$R_2 = AM_{2B} ,$$  \hspace{1cm} (7)

$$R_1 = AM_{1B} ,$$  \hspace{1cm} (8)

$$R_2 = CM_{2} + D ,$$  \hspace{1cm} (9)

$^3$ See http://exoplanet.eu.
Fig. 3.—Examples of binary systems analyzed in the present work. Here, and in Fig. 6, the light curves were smoothed to reduce noise and clarify visualization. The index c, when added to the CoRoT ID, indicates that the light curve was corrected from short-period oscillations. See the electronic edition of the PASP for a color version of this figure.
where equation (3) is Kepler’s third law, equations (4) and (5) are obtained by the transit best fit, and equations (6) and (7) are the empirical mass-radius relations used, depending on whether the secondary companion is a star or a planet. Therefore, two sets of five relations are numerically solved and two sets of the parameters $M_1$, $R_1$, $M_2$, $R_2$, and $a$ are computed. If $R_2 \gtrsim 2 R_{\text{Jup}}$, then we consider the system to be a binary candidate and the parameters yielded by equations (3), (4), (5), and (6) are used. On the other hand, if $R_2 < 2 R_{\text{Jup}}$, then the parameters yielded by equations (3), (4), (5), and (7) are used.

The numerical calculation of $M_1$, $R_1$, $M_2$, $R_2$, and $a$ proceeds as follows: First, one of the parameters is fixed (e.g., $M_1 = 1 M_\odot$) and the others are calculated. Then the ratio $a/R_1$ is compared with the value of $a_p$ provided by the transit best fit. The fixed parameter is iteratively incremented (or decremented) until the difference between $a/R_1$ and $a_p$ is as small as one wishes. When this condition is satisfied, the five parameters are finally estimated.

Concerning the mass of the secondary objects ($M_2$), there are three possibilities:

1. If the companion has $R_2 > 2 R_{\text{Jup}}$, then it will probably be a low-mass star and its mass can be easily estimated by the mass-radius relation fitted to that region of the diagram.
2. If $R_2 < 1 R_{\text{Jup}}$, then we can estimate a value for $M_2$ using the other mass-radius relation; however, since the mass-radius relation for planets depends on their chemical composition, it is not possible to estimate an accurate mass value for the secondary in this radius regime if its composition is unknown.
3. Finally, if $1 \leq R_2 \leq 2 R_{\text{Jup}}$, then the mass cannot be univocally determined, since—for one given radius—objects in this radius regime may have masses ranging from about $1 M_{\text{Jup}}$ to about $100 M_{\text{Jup}}$ (brown dwarfs).

Based on these arguments, in our discussion we only include a mass estimate for secondary companions with $R_2 \gtrsim 2 R_{\text{Jup}}$. Nevertheless, we note that our method provides a good estimate for the radius of not only primary and secondary stars, but also of planetary companions (even for $R_2 < 2 R_{\text{Jup}}$). Indeed, this is the case of the confirmed CoRoT systems, for which results are presented and discussed in § 4.

### 3.2. Uncertainties in the System Parameters

The results presented here are for the parameters $a$, $i$, $M_1$, $R_1$, $M_2$, and $R_2$, where $a$ is given in astronomical units, $M_1$ and $M_2$ are given in solar masses, $R_1$ is given in solar radii, and $R_2$ is given in Jupiter radii. To estimate the uncertainty in these parameters, the procedure is as follows:

1. First, the standard deviation ($\sigma$) is computed in a region outside a transit for the model that best fits the light curve; in a region inside a transit, a possible presence of spots on the surface of the primary star would cause variations in the light curve (Silva 2003) and $\sigma$ would be miscalculated.
The empirical mass-radius relations used by our method. The long-dashed line is a function given by eq. (1), fitted to stars (open circles), and the solid line represents a function given by eq. (2), fitted to known exoplanets (open squares) and the planets of the solar system (filled squares). Crosses represent exoplanets and low-mass objects that were not used in the fit (see text). The values of mass and radius were taken from the Extrasolar Planets Encyclopedia. See the electronic edition of the PASP for a color version of this figure.

2. By changing, at a given step, the three basic parameters yielded from the best fit to the transit ($R_p$, $a_p$, and $i$), we obtain a new light curve.

3. Next, these parameters are changed until the new light curve starts deviating significantly from the best one; that is when the difference between the light curves is more than $1\sigma$ for at least 10% of the transit.

4. Finally, these new basic parameters are used to reestimate $M_1$, $M_2$, $R_1$, and $R_2$ following the procedure described in § 3.1; the difference between both new and best estimates provides the uncertainties in the parameters.

Our mass-radius relations (eqs. [1] and [2]) do not depend directly on the orbital inclination angle. However, since a change in this parameter leads to a change in both depth and duration of the transit, its uncertainty can be included in the uncertainty determination of the other two basic parameters. To do so, first the uncertainty in the inclination angle is estimated as described previously (in steps 2 and 3, only $i$ is changed). Then, the uncertainties in the other two parameters (each one in turn) are estimated considering the inclination angle changed by its uncertainty. At the end, the uncertainties in $M_1$, $R_1$, $M_2$, and $R_2$ take into account those in $R_p$, $a_p$, and $i$.

The uncertainty in $a$ includes those in both $a_p$ and $R_1$, given the conversion of the semimajor axis from units of stellar radius to astronomical units.

To reduce noise and clarify visualization, a smoothing function was applied to the light curves before searching for the model that best fits the transit. In addition, for some systems only the best quality channels were used in the analysis. These procedures result in a more accurate estimate of the system parameters and, consequently, in smaller uncertainties.

### 4. RESULTS AND DISCUSSION

#### 4.1. Characterization of Binary System Candidates

Table 1 and Figure 3 show a few examples of our method applied to light curves of systems classified as eclipsing binaries or targets having faint background eclipsing binary stars.

#### Table 1

| CoRoT ID  | Run  | $P$ (days) | $a$ (AU)    | $i$ (deg) | $M_1$ ($M_\odot$) | $R_1$ ($R_\odot$) | $M_2$ ($M_\odot$) | $R_2$ ($R_\odot$) | Ref. |
|----------|------|------------|-------------|-----------|-------------------|-------------------|-------------------|-------------------|-----|
| 0102787048    | IRA01 | 7.896      | 0.094 ± 0.008 | 85.1 ± 0.2 | 1.63 ± 0.08 | 2.1 ± 0.2 | 0.16 ± 0.07 | 2.00 ± 0.31 | 2, 3, 4 |
| 0102811578    | IRA01 | 1.66882    | 0.0339 ± 0.0008 | 77.1 ± 0.2 | 1.57 ± 0.02 | 1.95 ± 0.04 | 0.32 ± 0.02 | 3.09 ± 0.17 | 2    |
| 0102815260    | IRA01 | 3.587      | 0.057 ± 0.006 | >87.0     | 1.71 ± 0.09 | 2.2 ± 0.2 | 0.19 ± 0.08 | 2.14 ± 0.31 | 2, 4 |
| 0102855534    | IRA01 | 21.72      | 0.218 ± 0.014 | 86.9 ± 0.2 | 2.48 ± 0.07 | 4.2 ± 0.2 | 0.50 ± 0.05 | 4.49 ± 0.42 | 2, 4 |
| 0100773735    | LRC01 | 4.974      | 0.074 ± 0.004 | 82.5 ± 0.2 | 1.98 ± 0.06 | 2.8 ± 0.1 | 0.23 ± 0.04 | 2.42 ± 0.24 | 1    |
| 0100868002    | LRC01 | 11.8054    | 0.136 ± 0.007 | 85.1 ± 0.1 | 2.02 ± 0.02 | 2.9 ± 0.1 | 0.42 ± 0.04 | 3.80 ± 0.31 | 1    |
| 0101482707    | LRC01 | 39.89      | 0.270 ± 0.004 | 88.5 ± 0.1 | 1.45 ± 0.01 | 1.73 ± 0.02 | 0.19 ± 0.01 | 2.18 ± 0.09 | 1    |
| 0101952846    | LRC01 | 79.95      | 0.41 ± 0.02   | >89.7     | 1.30 ± 0.05 | 1.46 ± 0.08 | 0.18 ± 0.06 | 2.10 ± 0.17 | 1    |
| 0211660858    | SRC01 | 8.825      | 0.114 ± 0.008 | 86.3 ± 0.3 | 2.12 ± 0.07 | 3.2 ± 0.2 | 0.46 ± 0.05 | 4.10 ± 0.38 | 1    |
| 0211654447    | SRC01 | 4.751      | 0.090 ± 0.005 | 70.9 ± 0.4 | 3.3 ± 0.1  | 7.4 ± 0.3 | 1.04 ± 0.10 | 9.90 ± 1.23 | 1    |
| 0102755587    | IRA01 | 27.955     | 0.28 ± 0.02   | 83.8 ± 0.2 | 3.4 ± 0.1  | 7.6 ± 0.4 | 0.48 ± 0.07 | 4.28 ± 0.61 | 1    |

Notes.—The uncertainties in $a$, $i$, $R_1$, $M_1$, $M_2$, and $R_2$ were estimated as described in § 3.2. These targets represent confirmed or probable binary systems and they are all discussed in § 4.1.

References.—(1) Cabrera et al. 2009; (2) Carpano et al. 2009; (3) Deeg et al. 2009; (4) Moutou et al. 2009.
| CoRoT ID       | Run | P (days)       | a (AU)       | i (deg) | M₁ (Mₖ) | R₁ (Rₖ) | R₂ (R_Jup) | Ref. |
|---------------|-----|----------------|--------------|---------|---------|---------|-----------|------|
| 0102890318    | IRA01 | 1.5089557 (64) | 0.027 ± 0.002 | 85.2 ± 0.5 | 1.11 ± 0.04 | 1.18 ± 0.06 | 1.59 ± 0.13 | 0    |
| 0102890318    | IRA01 | 1.5089557 (64) | 0.0254 ± 0.0004 | 85.1 ± 0.5 | 0.95 ± 0.15 | 1.11 ± 0.05 | 1.49 ± 0.08 | 1    |
| 0101206560    | LRe01 | 1.7429964 (17) | 0.028 ± 0.002 | 87.5 ± 0.4 | 0.90 ± 0.03 | 0.90 ± 0.04 | 1.38 ± 0.10 | 0    |
| 0101206560    | LRe01 | 1.7429964 (17) | 0.0281 ± 0.0009 | 87.8 ± 0.1 | 0.97 ± 0.06 | 0.902 ± 0.018 | 1.465 ± 0.029 | 2    |
| 0101368192    | LRe01 | 4.256800 (5)   | 0.056 ± 0.005 | 86.3 ± 0.4 | 1.33 ± 0.07 | 1.52 ± 0.11 | 0.98 ± 0.13 | 0    |
| 0101368192    | LRe01 | 4.256800 (5)   | 0.057 ± 0.003 | 85.9 ± 0.8 | 1.37 ± 0.09 | 1.56 ± 0.09 | 1.01 ± 0.07 | 3    |
| 0102912369    | IRA01 | 9.20205 (37)   | >89:3        | 1.03 ± 0.04 | 1.07 ± 0.06 | 1.07 ± 0.10 | 0      | 0    |
| 0102912369    | IRA01 | 9.20205 (37)   | >89:915      | 1.16 ± 0.03 | 1.17 ± 0.03 | 1.19 ± 0.06 | 4      | 0    |
| 0102764809    | LRA01 | 4.0378962 (19) | 0.053 ± 0.003 | 85.0 ± 0.2 | 1.19 ± 0.04 | 1.29 ± 0.06 | 1.37 ± 0.14 | 0    |
| 0102764809    | LRA01 | 4.0378962 (19) | 0.04947 ± 0.00029 | 86 ± 1 | 1.00 ± 0.02 | 1.19 ± 0.04 | 1.388 ± 0.047 | 5    |
| 0106017681    | LRe02 | 8.886593 (4)   | 0.053 ± 0.006 | 89.4 ± 0.4 | 0.96 ± 0.05 | 0.98 ± 0.06 | 1.06 ± 0.10 | 0    |
| 0106017681    | LRe02 | 8.886593 (4)   | 0.055 ± 0.0015 | 89.1 ± 0.3 | 1.05 ± 0.05 | 1.025 ± 0.026 | 1.166 ± 0.035 | 6    |
| 0102708694    | LRA01 | 0.853585 (24)  | 0.018 ± 0.005 | 78.2 ± 1.5 | 0.98 ± 0.17 | 1.01 ± 0.23 | 0.15 ± 0.07 | 0    |
| 0102708694    | LRA01 | 0.853585 (24)  | 0.01720 ± 0.00029 | 80.1 ± 0.3 | 0.75 ± 0.03 | 0.87 ± 0.04 | 1.50 ± 0.008 | 7    |
| 0101086161    | LRe01 | 6.21229 (3)    | 0.067 ± 0.004 | 86.7 ± 0.1 | 1.06 ± 0.03 | 1.11 ± 0.05 | 0.88 ± 0.09 | 0    |
| 0101086161    | LRe01 | 6.21229 (3)    | 0.063 ± 0.001 | 88.4 ± 0.1 | 0.88 ± 0.04 | 0.77 ± 0.02 | 0.57 ± 0.02 | 8    |
| 0105891283    | LRe02 | 95.2738 (14)   | 0.39 ± 0.02   | >89:87 | 0.85 ± 0.03 | 0.84 ± 0.04 | 0.93 ± 0.08 | 0    |
| 0105891283    | LRe02 | 95.2738 (14)   | 0.407 ± 0.005 | >89:95 | 0.99 ± 0.04 | 0.94 ± 0.04 | 1.05 ± 0.04 | 9    |
| 0100725706    | LRe01 | 13.2406 (2)    | 0.108 ± 0.005 | 88.0 ± 0.1 | 0.94 ± 0.03 | 0.95 ± 0.04 | 1.15 ± 0.10 | 0    |
| 0100725706    | LRe01 | 13.2406 (2)    | 0.1055 ± 0.0021 | 88.6 ± 0.1 | 0.89 ± 0.05 | 0.79 ± 0.05 | 0.97 ± 0.07 | 10   |
| 0105833549    | LRe02 | 2.994330 (11)  | 0.044 ± 0.002 | 83.2 ± 0.2 | 1.24 ± 0.04 | 1.37 ± 0.06 | 1.32 ± 0.13 | 0    |
| 0105833549    | LRe02 | 2.994330 (11)  | 0.044 ± 0.005 | 83.17 ± 0.15 | 1.27 ± 0.05 | 1.37 ± 0.03 | 1.43 ± 0.03 | 11   |
| 0102671819    | LRA01 | 2.828042 (13)  | 0.040 ± 0.003 | 85.7 ± 0.2 | 1.02 ± 0.05 | 1.06 ± 0.07 | 1.33 ± 0.15 | 0    |
| 0102671819    | LRA01 | 2.828042 (13)  | 0.0402 ± 0.0009 | 85.5 ± 0.8 | 1.08 ± 0.08 | 1.12 ± 0.10 | 1.44 ± 0.13 | 12   |

Notes.—The period values and their uncertainties (shown in parentheses for the last significant digits) are from the respective announcement articles. The uncertainties in a, i, M₁, R₁, and R₂ were estimated as described in § 3.2.

References.—(0) this work; (1) CoRoT-1: Barge et al. 2008; (2) CoRoT-2: Alonso et al. 2008; (3) CoRoT-3: Deleuil et al. 2008; (4) CoRoT-4: Aigrain et al. 2008; (5) CoRoT-5: Rauer et al. 2009; (6) CoRoT-6: Fridlund et al. 2010; (7) CoRoT-7: Léger et al. 2009; (8) CoRoT-8: Bordé et al. 2010; (9) CoRoT-9: Deeg et al. 2010; (10) CoRoT-10: Bonomo et al. 2010; (11) CoRoT-11: Gandolfi et al. 2010; (12) CoRoT-12: Gillon et al. 2010.
According to Silva & Cruz (2006), the present method should consider as nonplanetary candidates only the systems for which the radius of the secondary companion is larger than 1.5 Jupiter radii. After that publication, some exoplanets with radius between 1.5 and 2 \( R_{\text{Jup}} \) were discovered. Thus, in this work, we chose a more conservative value of \( R_2 = 2 \ R_{\text{Jup}} \) for the lower limit of binary candidates.

The systems that our method classifies as binary candidates actually represent classes of systems with different configurations of the components. There are several sources of false alarms that can mimic the transit of a planet in front of the main target. The most common are eclipsing binary systems with grazing transits, targets having a background eclipsing binary system, or even triple systems. The present method does not identify the exact configuration of the system, but provides the information that the observed transits are likely not caused by a planet. Listed next are our comments for each case. The window ID of the run (e.g., E1-0288) is also shown as a complementary identifier.

4.1.1. IRa01—0102787048 (E1-0288)

This system was first classified by Carpano et al. (2009) as a planetary transit candidate. However, after follow-up observations, Moutou et al. (2009) confirmed that the transit is originated by a background eclipsing binary and then diluted by the main target. They estimated a mass ratio of 0.15 between secondary and primary components of the binary system. Using the results of our method we have a value of 0.10 \pm 0.04 for the same ratio, which is consistent with a diluted transit of a more massive object. The fact that no transit is observed in the red channel also helped to label a nonplanetary nature for this target.

4.1.2. IRa01—0102811578 (E2-0416)

System classified by Carpano et al. (2009) as an eclipsing binary. No information concerning follow-up observations has been published. Our estimate of mass and radius for the secondary companion confirms its binary nature.

4.1.3. IRa01—0102815260 (E2-2430)

Also in the list of planetary transit candidates of Carpano et al. (2009), but afterward classified by Moutou et al. (2009) as a binary system according to radial-velocity observations. Our estimate for the mass ratio is 0.11 \pm 0.04, slightly smaller than the value of 0.17 published by Moutou et al. (2009), but still consistent with a stellar companion.

4.1.4. IRa01—0102855534 (E2-1736)

Follow-up observations conducted by Moutou et al. (2009) indicate that an eclipsing binary is the main target, changing the planetary nature of the secondary first suggested by Carpano et al. (2009). The radial-velocity measurements indicate a mass ratio of 0.2, which agrees with our estimate of 0.19 \pm 0.01. In-deed, the mass and radius that we show in Table 1 clearly indicate the stellar nature of the secondary.

4.1.5. LRc01—0100773735 (E2-1245)

Based on radial-velocity observations, Cabrera et al. (2009) suggest that this is a spectroscopic binary or multiple system. Our mass and radius estimate confirms their conclusion of a nonplanetary object causing the observed transits.

4.1.6. LRc01—0100885002 (E2-4653)

This target is listed in Cabrera et al. (2009) as an eclipsing binary, which is in agreement with the mass and radius estimated using our method. Transits are observed only in the blue channel, contributing to the classification of this system as nonplanetary.

4.1.7. LRc01—0101482707 (E1-2837)

Also classified by Cabrera et al. (2009) as a binary system after radial-velocity observations and confirmed by our method.

4.1.8. LRc01—0101434308 (E1-3425)

Cabrera et al. (2009), without doing any follow-up observations, concluded that this is a binary system, given the fact that the transit is predominantly seen in the blue channel.

Table 1 also lists our results for the targets 0211660858 (SRe01, E2-0369), 0211654447 (SRe01, E1-1165), and 0102755837 (LRa01, E2-2249). The CoRoT team has not yet published the results of their analysis for these runs. Nevertheless, they are shown here, because the secondary mass and radius estimated by our method clearly classify these targets as nonplanetary systems.

As one can see in Table 1, for some targets the estimated radius of the secondary companion is close to the limit of 2 \( R_{\text{Jup}} \) used to distinguish binaries from possible planetary systems. They were classified as probable binary systems considering that, at present, all detected exoplanets for which the radius was derived are as large as 1.8 \( R_{\text{Jup}} \) or smaller.

Among the nine targets listed in Table 1 that were analyzed and published by the CoRoT team, six were classified as binary systems only after ground-based follow-up, either by radial-velocity measurements, or by photometric observations, or both. This is an indication that the method normally used by different CoRoT working groups is perhaps not good enough to provide a preclassification of the targets. Our method would exclude the binary targets by itself, and no time-consuming follow-up observations would be required for most cases.

4.2. Characterization of Exoplanetary Systems

Table 2 presents our parameter estimates for confirmed CoRoT exoplanetary systems, from CoRoT-1 through 12, together with the results presented in the announcement articles. Here, the method uses the information provided by the mass-radius
Fig. 6.—First six CoRoT exoplanetary systems: CoRoT-1 through CoRoT-6, respectively, from left to right and from top to bottom. See the electronic edition of the PASP for a color version of this figure.
relation fitted to known transiting exoplanets and to the planets of the solar system (eq. [2], Fig. 5). Figure 6 shows the light curves of the first six CoRoT systems plotted with our best fit. The results of a detailed comparison between our estimates and those of the announcement articles are shown in Table 3. This table lists the coefficients of weighted linear regressions obtained for \( a, i, M_1, R_1, \) and \( R_2, \) where the weights \( 1/\sigma^2 \) were used for \( \sigma \) representing the errors that we estimated for these parameters. At first, we computed the coefficients using the first 12 CoRoT systems and no systematic difference was found within \( 2\sigma. \) Within \( 1\sigma, \) however, the agreement is not so good, especially for \( M_1 \) and \( R_1. \) This is mostly due to discrepancies in the comparison of CoRoT-8, as one can observe in Table 2. The data points in the light curve of this system have a dispersion of 0.017, which is much larger than those of the other CoRoT systems: \( \sim 0.007 \) or smaller. Indeed, if the parameters of CoRoT-8 are not included in the regressions, the agreement between our results and those of the announcement articles is much better. An extra caution when dealing with noisy light curves is therefore recommended. Light curves with small-depth or long-period transits (such as CoRoT-7 and 9, respectively) also produce larger uncertainties in the parameters and should be carefully analyzed.

In Table 2, all planets detected in the CoRoT field have \( R_2 < 1.5 R_{\text{Jup}}, \) also including our estimate for CoRoT-1 if we take its uncertainty into account. This result supports our suggestion that the present method can be used to characterize not only systems for which the radius of the secondary companion is larger than \( 2 R_{\text{Jup}}, \) but also those having \( R_2 \) smaller than \( 1.5 R_{\text{Jup}}, \) helping as a complementary approach in the search of promising candidates for radial-velocity follow-up. The intermediate situations, when \( R_2 \) stands between 1.5 and \( 2 R_{\text{Jup}}, \) are not conclusive.

## 5. Conclusions

We have presented a method that provides a good estimate of some physical and orbital parameters of a transiting system, such as the mass and radius of the secondary companion. Applied to transiting light curves, the method will exclude cases that are most probably related to low-mass stars in a binary system, instead of a planet. In other words, our method is able to exclude systems that may be considered as good planetary candidates at first, but that would have their binary nature unveiled afterward, without making use of time-consuming ground-based measurements that are normally conducted to complement the observations.

We note that the method does not, by itself, determine the real nature of the secondary object (whether it is a binary companion or not). Instead, it identifies and characterizes probable candidates for binary systems, which will help to reduce the huge number of targets that are initially available and to create a list of priority stars, still candidates for planetary systems, to be monitored with radial-velocity measurements. We do not discard other methods, however, which can be used to complement our approach.

The method was also applied to 12 CoRoT targets confirmed as planetary systems, showing that the estimated radii of the secondary companions (as well as other orbital parameters) are in very good agreement with the results published by the respective announcement articles. This means that our model can also be used in the characterization of possible exoplanetary systems, especially when \( R_2 \) is smaller than or of the order of \( 1.5 R_{\text{Jup}}. \) No conclusions could be drawn concerning the radius range \( 1.5 < R_2 < 2 R_{\text{Jup}}. \)

Our model is useful not only to be applied to CoRoT light curves that have been or will be released by the mission, but also to data of other present or future missions based on photometric observations of transiting systems that involve a large sample of targets (such as the Kepler mission).

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