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Expected Performance of the CoRoT Planet Search from Light Curve Beauty Contests

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Abstract. The CoRoT space mission, scheduled for launch in December 2006, has two primary science goals: asteroseismology and the detection of planetary transits, the latter being the subject of this contribution. Given its expected photometric performance and its 150 day observing window, CoRoT will detect planets with periods up to 75 days and radii down to 2 Earth radii. To prepare for the data analysis and evaluate the detection limits of the mission, a number of blind exercises to detect planets in simulated light curves have been carried out within the CoRoT exoplanet community, and their results to date are summarized here.

Presentation of CoRoT

The CoRoT space mission (Baglin et al. 2007) will be launched in December 2006 by a Soyuz rocket from Baikonour. It is devoted to asteroseismology and transit search, with a two-beam telescope and a different strategy in each channel. It will open a new path towards the study of transiting planets of small size, and explore the domain of "hot Uranus" planets, which appears from recent radial velocity surveys to be crowded (see for example Lovis et al. 2006).
CoRoT has an off-axis telescope mount with a primary of equivalent diameter 27 cm. The field of view for planet search is $3.9^{\circ 2}$. The planet search optical path is equipped with a biprism which spreads the light on a low-resolution spectrum on the detector. Each star image expands on 5 to 15 pixels in the direction of the dispersion, with a pixel size of 2.3". This dispersive device will allow a first level analysis of the stellar light curves, including a positional discrimination capacity (only the central object would have a transit event equivalent in all channels), and a differential chromatic signature (stronger for stellar variability

and eclipsing binaries than planetary transits).

The magnitude range of CoRoT targets is 11.5 to 15.5. The targets are selected within sky areas that are inside the "CoRoT eyes" of 10° radius: (RA=18h50, DEC=0°) in the April to October observing seasons, and (RA=6h50, DEC=0°) in the October to April observing seasons. During a single season of 150 days, 12000 stars will be observed continuously. After 3 years, the nominal mission lifetime, more than 70,000 stars will have been monitored with 8 minute sampling. Photometry is performed on-board using predefined aperture masks. Coloured light curves will be registered for 80% of the targets. The expected performance of CoRoT transit detection has been discussed from the basis of theoretical instrumental and stellar properties in Bordé et al. (2003). It relies on the specified photometric accuracy of CoRoT in the exoplanet chanel, i.e. a 10^{-4} precision for a 13th magnitude solar-type star in one hour. We present here a more empirical approach to this performance estimation, based on simulated light curves and compared detrending and detection algorithms, for which all details are given in Moutou et al. (2005).

Blind test exercises

The scheme of the CoRoT blind test exercises is the following: 1) creation of simulated light curves including realistic instrumental noises (as known before launch), realistic stellar microvariability, and signatures of planetary transits and eclipsing binaries (diluted or not); 2) distribution of the light curve set to the whole detection group of CoRoT, with very basic information (star magnitude and color); 3) independent analyses of the light curves; 4) confrontation to real light curve contents; 5) fine tuning of algorithms for an optimization of the detection and/or characterization capacity.

Lightcurve simulation

The first set of 1,000 simulated light curves contains all components of CoRoT noises, at the residual level expected after proper data processing. The noise source considered as dominant in the regime of transit search is the residual light scattered by the Earth and not rejected by the CoRoT baffle. Its signal is quasi-periodic with the satellite orbit, but with an amplitude varying over the detector field-of-view. Thus, a small differential residual pattern was included in the simulated light curves, corresponding to over- or under-estimated corrections of the scattered light, having a potential impact on the detection of real events and false positives (see Fig. 1).

Another characteristics of CoRoT light curves that detection algorithms have to face is the presence of periodic gaps in the data, corresponding to the crossing of the South Atlantic Anomaly. The detector is set off during these periods, totaling up to 30 min every 1.7 hour.

The star photometric micro-activity is considered as a noise source from the point of view of planetary transit detection. The temporal properties of stellar micro-activity was simulated for several types of targets, depending on the stellar mass and age (or rotation period). Two approaches were considered, one scaling a solar model made of three active regions on a uniform background

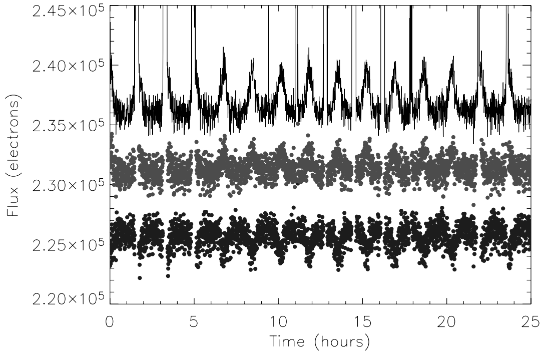

Figure 1. The residual amplitude of the scattered light (top) is either positive (middle), or negative (bottom). Such effect is probably conservatively high in our simulation and might be better corrected for in real CoRoT light curves.

(Lanza et al. 2003), and one computing a power spectrum based on the Sun and scaled with empirical laws (Aigrain et al. 2004). Transits events caused by planets or binary stars have been computed using the Universal Transit Modeler, Nightfall and the routines of Mandel & Agol (2002). Transits were inserted in part of the light curves only, with characteristics chosen to test the limitations and to explore the borders of the detection space. The light curves without transit event still vastly outnumber those with transits, so that the detection thresholds have to be put realistically high and false positive statistics is not artificially changed.

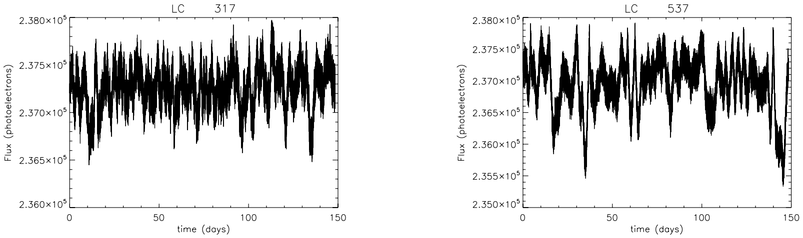

Figure 2. Two example simulated light curves: *left*: a bright, relatively quiet F5 type star with a 2.2 Earth radius, 33.8 day period planet; *right*: a bright, active K star with a inflated hot Jupiter planet. This second event was detected despite the large amplitude of stellar variability, while the first case is seemingly below the detection capacity of CoRoT, as characterized from the simulation (Moutou et al. 2005).

In a second exercise, more than 200 light curves were simulated using the same approach, and considering the splitting into three "filters", as obtained in the colour mode of CoRoT photometry. A transit event was included in all light curves, with a correct proportion between planetary and stellar events.

The objective there was to test our ability of characterizing the planetary events from the light curve analysis only, and to evaluate the required effort in follow-up observations.

Detrending and detection

Several algorithms were tested by the independent teams (details are given in Moutou et al. (2005)). These different methods scan a wide range of complexity. The detrending methods included high- and low-pass filtering, linear fits to short sections of data, detrending based on image processing techniques (Guis & Barge 2005), removal of low-frequency harmonics, and an iterative non-linear filter (Aigrain & Irwin 2004). The detection methods included a simple correlation with a sliding transit template, matched filters, and several methods based on least-squares fitting of box-shaped transits (Kovàcs et al. 2002). The exercise highlighted a number of interesting points. First, even the simplest methods are effective for the most significant events. Second, the harmonics removal method and the iterative non-linear filter were most effective in removing stellar micro-variability, which should not limit the detection performance of CoRoT except in the most extreme cases. Third, the best detection performance was obtained with box least-squares methods. Finally, a very promising result is that false alarms by two separate teams in the same light curve never coincided, indicating that false alarms may be minimized by combining results from several approaches. Finally, the detection performance in terms of planetary radius has been estimated from this exercise. The smallest detected planetary radius clearly depends on the star (radius, magnitude and level of variability) and on the orbital period. We could derive an empirical law relating the transit depth d and the number of transits n: $d = 2.10^{-3} n^{-1/2}$. Table 1 and Figure 3 also show this result. As an example, CoRoT would detect the transit of a planet like μ Ara d (14.5 Earth masses and 9.5 day period, Santos et al. 2004), if its density is that of a terrestrial planet. For the brightest stars, CoRoT and its spectroscopic follow-up will be able to distinguish between a gaseous, ocean or telluric planet in the mass regime of Uranus or slightly below (Selsis et al., in press), opening a new area of exoplanetology investigations.

Table 1. Minimum planet radius for F0V, G0V, K0V, and M0V stars in unit of Earth radius, corresponding to the empirical detection curve estimated by the blind test.

Period	F0V	G0V	K0V	M0V
50-day	5.6	4.0	3.2	2.2
10-day	3.75	2.75	2.1	1.5
3-day	2.8	2.0	1.6	1.1

Characterization

A second test was initiated in 2006 to estimate our ability to characterize the transits from the light curve analysis alone, and to disentangle planetary events from several kinds of eclipsing binary events. Three light curves per star were

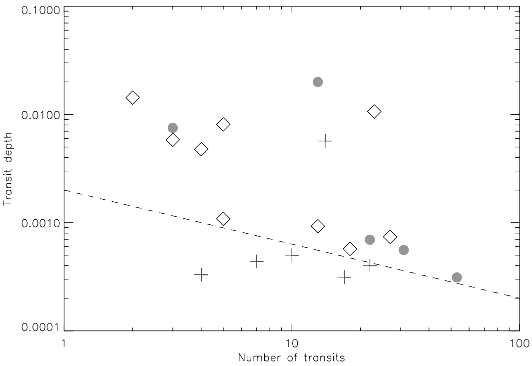

Figure 3. Depth of the transits versus number of transits. Plus signs show the non-detected events, diamonds show the events detected by five groups independently, and filled circles correspond to detections by 1-4 groups. The dashed line thus shows the border of the simulated CoRoT detection limit (proportional to $n^{-1/2}$). The only plus sign above the detection line is a grazing planet on a faint fluctuating star.

calculated, corresponding to the blue, green and red channels obtained through the biprism and an adapted photometric mask. Although definitive conclusions are not yet derived at the time of writing, we may discuss preliminary hints from this test:

-Detrending and detection steps were usually performed on the white light curves (total flux of the three channels) where the signal-to-noise ratio is the largest
-The best performing detection is again obtained with box-shaped methods
-Many detections were correct, with part of them affected by a factor of two in the period estimation, with respect to the physical period of the simulated system: the eclipsing binary contamination may induce such confusion, when both eclipses are similar (within the noise amplitude)
-Several characterization methods were tested: search for a secondary transit, search for out-of-transit ellipsoidal variations, comparison of signal in coloured channels, transit shape, transit duration, η parameter (Tingley & Sackett 2005)
-The most robust parameter to distinguish contaminating eclipsing binaries is the detection of the secondary eclipse and/or ellipsoidal variations
-Simple tests based on a basic parametrization of the transit (such as the η-parameter) are dangerous when used without a full error analysis
-When a planet-candidate has passed the white-light tests, then tests based on the colors are useful. This must be used with care, as the presence of a background star in one of the channels may dilute the planetary transit and then mimic a chromatic effect. However, the position, magnitude and color of these contaminant stars is known from preparatory observations, and it will be possible to evaluate the flux contribution from contaminants in each channel before applying chromatic criteria
-Yes/no answers in rejection tests should be avoided due to the presence of

many borderline cases. Designing tests that result in a punctuation pending on a candidate's planet-likeliness, with a weighted combination of individual tests' results lead to more reliable classifications
-The information on the contaminant stars makes it possible to test whether the detected event is more likely a deep eclipse on a contaminant (blended eclipsing binary) or a planetary transit on the main target
-The most critical contamination finally comes from eclipsing binaries with large mass ratios. Follow-up observations are required to distinguish these scenarii from the searched transiting planetary system, unless the transit shape is determined with a very high signal-to-noise ratio.

Conclusions

The results of the "real size" blind test exercise performed in the context of CoRoT may well be extrapolated to other transit search programs, except for the characteristics which are proper to CoRoT, as some noise sources and the color information. The comparison of independent detrending and detection algorithms on a realistic data set is a rich complement to theoretical comparisons as done by Tingley (2003). The conclusions of our blind test comfort the conclusions of these other studies, i.e. that box-shaped detection is best optimized to detect the shallowest events. It also shows that false detections are not a major problem when several methods are applied. The stellar micro-variability (within the limitations of current models, which the CoRoT data itself will provide the first real test of) limits the detection only when its standard deviation is of more than 0.5% and frequency about 0.1 day^{-1}. The only type of systematic effect included in the blind exercise was incompletely corrected scattered light, but other, unforeseen systematics may occur in the real data. Methods based on the comparison of the global data set should be implemented to gain precision (Tamuz et al. 2005). Common rejection methods on white light data such as the search for secondary transits, ellipsoidal variation and characterization of the transit parameters are able to detect the majority of false alarms. The colour and position information encoded in the three CoRoT channels may be used as a further tool to distinguish planet transits from diluted eclipsing binaries. This nevertheless requires a profound analysis of the stellar content of the target PSF.

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