EXOTRANS detection pipeline ready to face the challenge to hunt and characterize exoplanetary systems in upcoming space missions

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Planeten forschung RIU

CoRoT

Abstract

In 2005 the Rheinisches Institut für Umweltforschung, Abteilung Planetenforschung at the University of Cologne (RIU-PF) developed EXOTRANS a pipeline for the detection of extrasolar planets for the CoRoT space mission. This pipeline was in use throughout the complete operation phase of CoRoT. During the mission many lessons were learned and even today the pipeline evolves continuously. Starting with two filters (trend and harmonic) and a BLS algorithm (box least square) great importance was attached to a high grade of automatization. Therefore we can deal with the huge amount of data produced by space missions like CoRoT, Kepler and even bigger upcoming missions. Challenges during the mission triggered the development of new algorithms.
Our wavelet based filter routine VARLET was developed to separate star variability and discontinuities in light curves. Detected binaries and planetary transits are extracted out of the light curve with PHALET to search for multi-planet systems.
EXOTRANS was applied to all Kepler data that were public in August 2012. We detected 98% of all candidates found by the Kepler team and detected even 143 new candidates not included in the Kepler candidate list (from January 2013).
Over time our focus has changed from detection only to detection and characterization of planetary transit candidates. This is important to rule out false positives, to find the best targets for follow-up observation and to build a solid foundation for statistical analysis. Stellar binaries are simulated to exclude false detections and to classify detected binary systems. Precise measurements and simulations of transit timing variations (TTV) are used to confirm planetary candidates and to constrain the system parameters. Comparisons between the simulated light curves and the measurements enables to extract the parameters of the planetary system.
A new numerical light curve simulator is under development to reproduce stellar atmospheres, starspots, planets, moons and rings.

Introduction

When CoRoT was started in 2006 we entered a new era of exoplanet detection. Continuous light curves with to this date unknown precision opened the possibility to search 10.000 stars per run for exoplanets. To search this huge amount of data for planetary candidates an automatic data pipeline was needed to filter all light curves and to detect planetary candidates. RIU-PF, one of the CoRoT detection teams, has developed the automatic detection pipeline EXOTRANS (Fig. 1) (Grziwa et al. 2012).
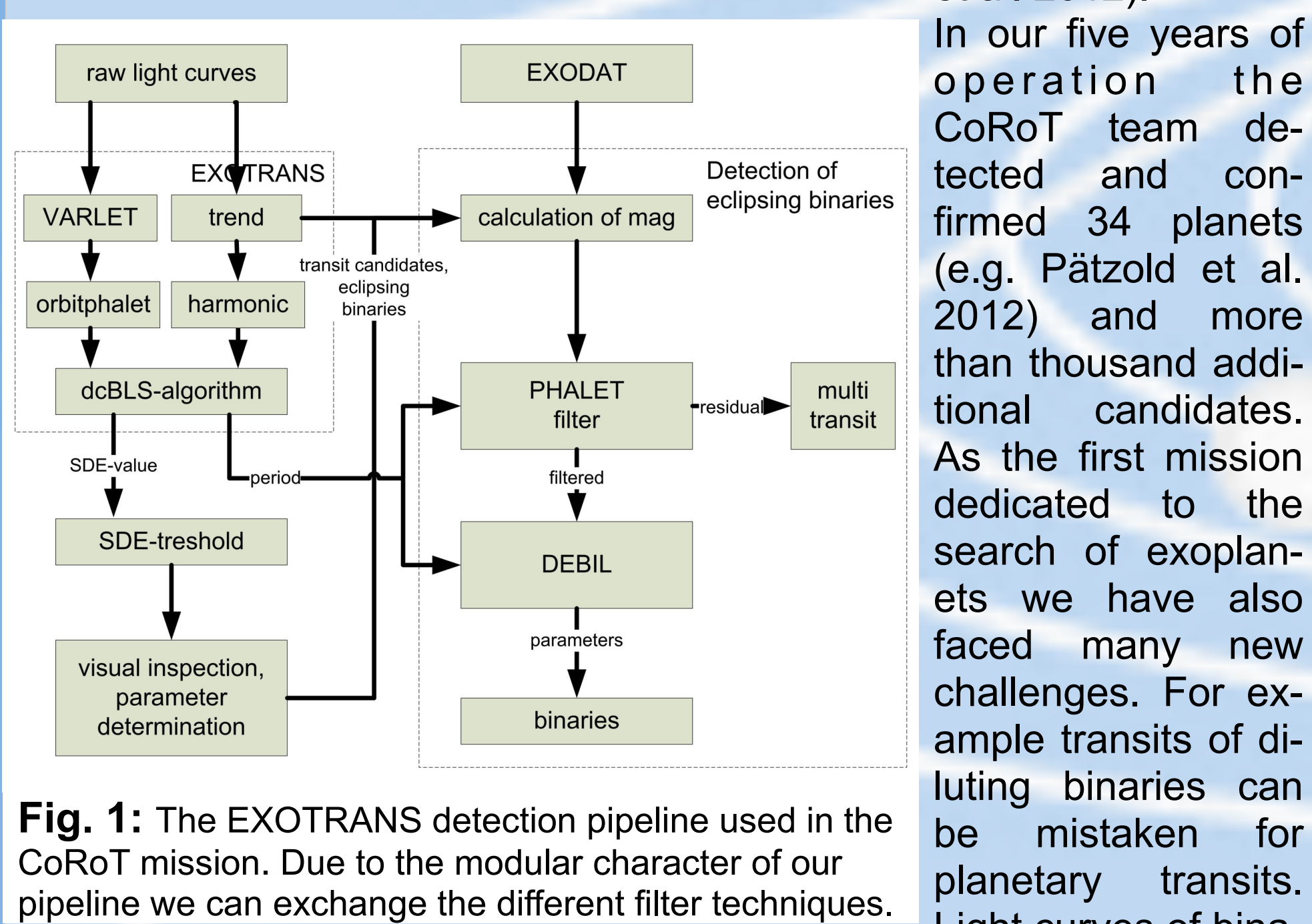
In our five years of operation the CoRoT team detected and confirmed 34 planets (e.g. Pätzold et al. 2012) and more than thousand additional candidates. As the first mission dedicated to the search of exoplanets we have also faced many new challenges. For example transits of diluting binaries can be mistaken for planetary transits. Light curves of binaries are therefore simulated to calculate the probability of binaries (Grziwa et al. 2011). Transits are extracted out of the light curves to search for multi planet systems. Hot pixels, jumps and stellar variations disturb the light curve and prevent the detection of transiting planets. These difficulties required the improvement of the detection pipeline and triggered the development of a new filter technique: VARLET.

Fig. 1: The EXOTRANS detection pipeline used in the CoRoT mission. Due to the modular character of our pipeline we can exchange the different filter techniques.

VARLET

The intrinsic variability of a star is a composition of a high number of disturbances at different frequencies and amplitudes changing over time. Simple low-pass, high-pass or band-pass-filters cannot eliminate these disturbances completely. Artefacts remain in the light curves. These artefacts can lead to false detections of transits when searched by a Box-fitting-Least-Squares algorithm (BLS) (Kovacs 2005).
A new wavelet based filter technique, VARLET, has been developed which was added to our CoRoT pipeline in January of 2012. The filter separates the stellar induced variability from the white noise and the transit. Figure 2 shows a highly variable Kepler light curve (top panel). This light curve is filtered by VARLET and separated in two parts: one including star variability (middle panel) and another one including white noise and possible transits (bottom panel). The scale of variability is extremely reduced. Deep transits of eclipsing binaries are also separated. The filtered light curve was searched by the BLS algorithm and a new candidate was found. Fig. 2 (right box) shows the transit of the new candidate phasefolded with the detected period of 1.21 days.
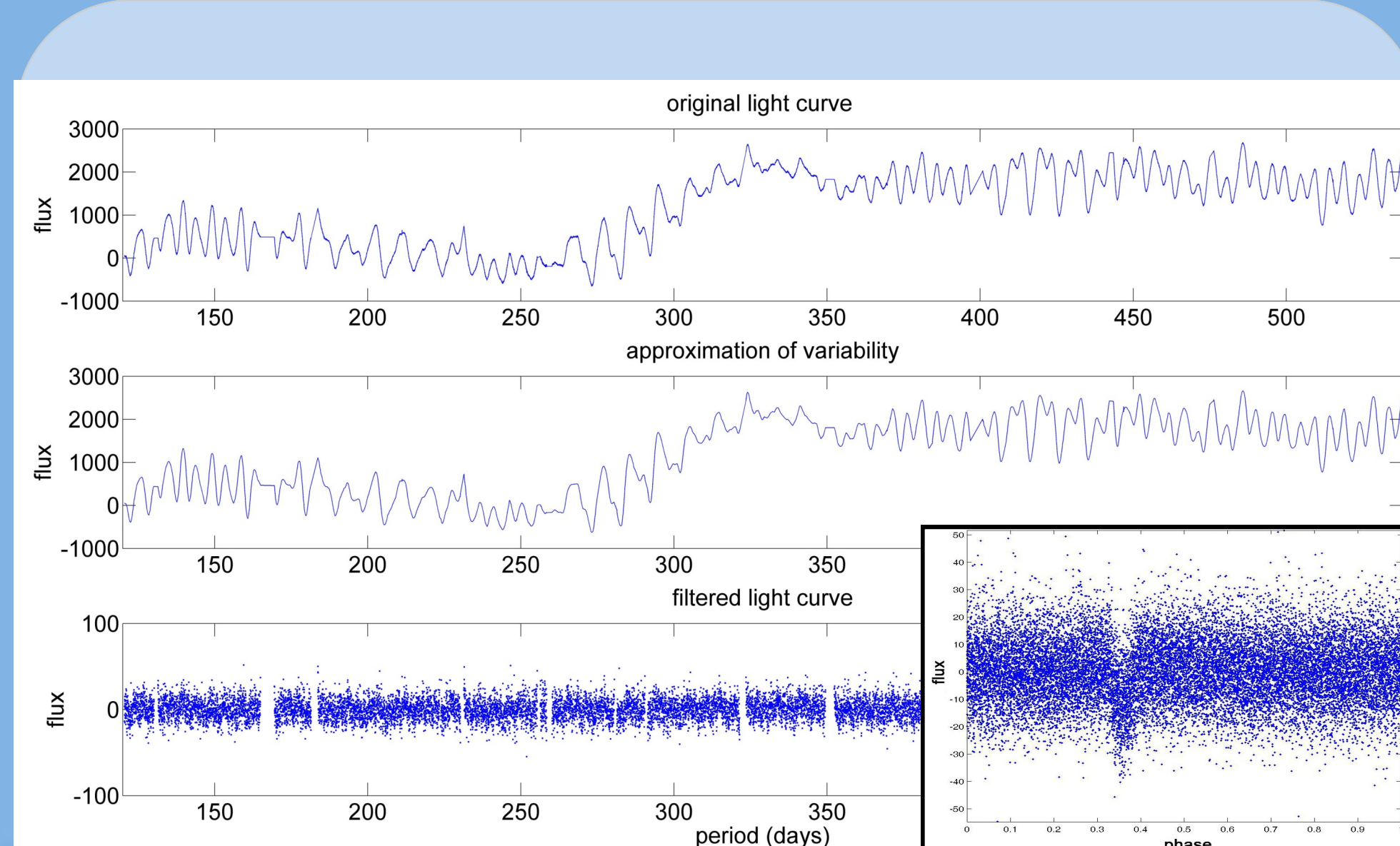

Fig. 2: The VARLET filter: (top) One of the more variable raw Kepler light curve. All quarters are combined in a single light curve. (middle) The approximation of the variability of the light curve found by VARLET. (bottom) The filtered light curve includes only white noise and the transit. The box on the right shows the light curve, phasefolded with the detected period of 1.207 days.

Processing public Kepler light curves

All nine quarters of the 150.000 public available Kepler light curves were combined. These light curves were filtered with VARLET and searched by our improved dcBLS algorithm using a search period between 0.8 and 75 days. After automated selection of promising candidates by the pipeline, the remaining candidates were checked for false positives (e.g. EB's and CB's) and the transits were characterized.
In August 2012 we compared our list of candidates and binaries to the list of 2320 candidates published by the Kepler team (Grziwa et al. 2011). Our pipeline detected more than 98% of all published Kepler candidate systems (KOI). Additionally, we found 786 undetected transit events that were undetected at this time (Fig. 3, left) with 219 new high rank candidates. In January 2013 this list was compared to the new improved Kepler candidate list (Fig. 3, right). 72 of the previously unknown candidates were now also detected by the Kepler team and 37 candidates of our candidates were identified as false positives. 143 high rank candidates of our list remain unidentified by the Kepler team.
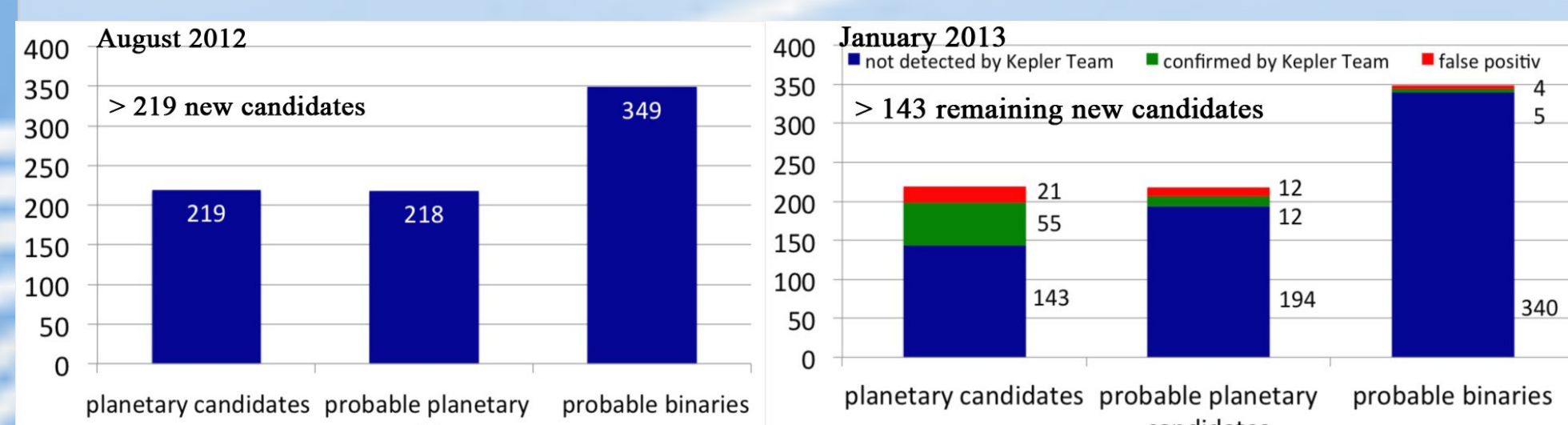

Fig. 3: Candidates detected by EXOTRANS not included in the Kepler candidate list. **Left:** more than 219 additional candidates found in August 2012. **Right:** same candidates compared to the new Kepler candidate list published January 2013. 143 candidates remain unidentified.

Transit Time Variation (TTV)

Transit Time Variation (TTV) describes the variation of the observed transit time from the calculated constant periodic time of the planetary transit. The dominating factor for this transit timing variation is the attracting force of additional bodies in the same system. This method can therefore be used to confirm planetary candidates detected by transit. It also enables to rule out alleged candidates and to constrain parameters of multi planet systems.
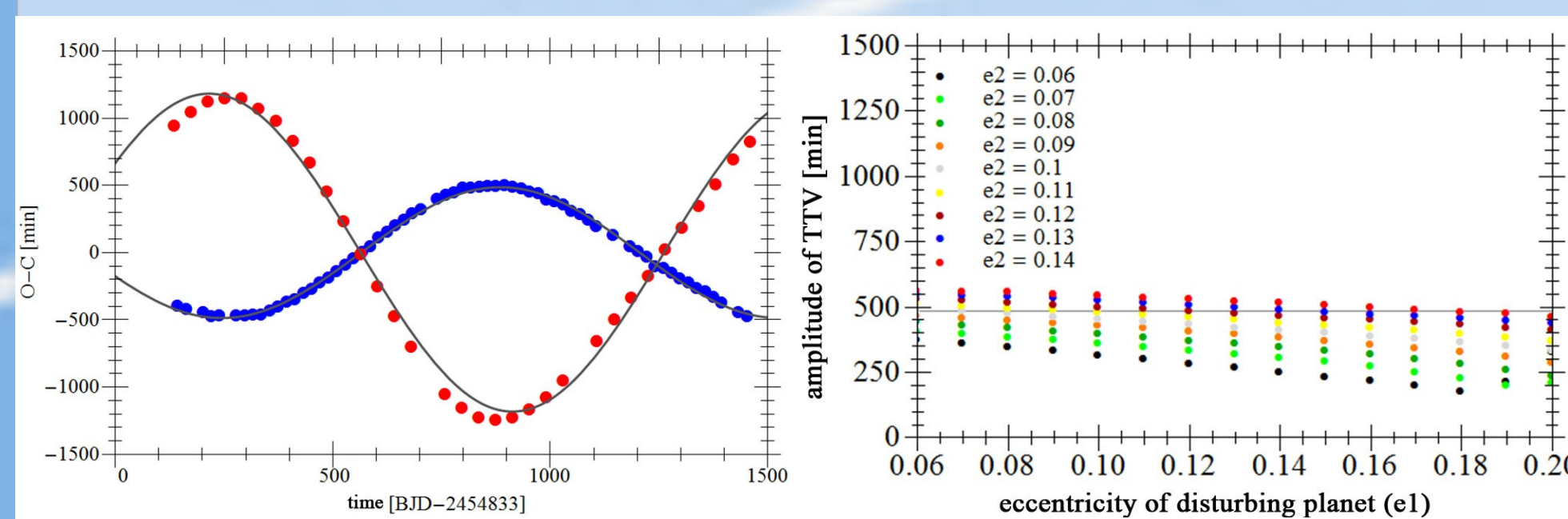

Fig. 4: Left: our measured O-C of Kepler-9b (blue) and Kepler-9c (red) plotted against time. **Right:** TTV amplitude of Kepler-9b simulated for different orbit eccentricities e1 (Kepler-9c) and e2 (Kepler-9b). The gray line shows solutions for our measured TTV amplitude of Kepler-9b (left).

RIU-PF developed a pipeline to analyse TTV very precisely and to determine the orbit parameters of multiplanet systems. Fig. 4 shows our results for the Kepler 9 system which was confirmed by TTV (Holman et al. 2010). The mid-transit times are measured using a modified version of the transit characterization tool TAP (Gazak et al. 2012). TAP uses a Monte-Carlo simulation to find the best Mandel & Agol model (Mandel & Agol 2002) for the combined transits. This model is fitted to every single transit to calculate the mid-transit times. Using this method the errors of the mid-transit times of Kepler 9b are reduced to 4 minutes. Fig. 4, left shows the difference between the calculated and the observed (O-C) transit times. The high precision of the resulting calculated O-C times is clearly visible in Fig. 4, left. The mean period is calculated by varying the period until the best sinus fit to the O-C times is found. By using all public Kepler light curves a more precise period of 19.2466 days for Kepler-9b and 38.9569 days for Kepler-9c than Holman et al. in 2010 could be determined
(Kepler-9b: 19.2431 days, Kepler-9c: 38.9569 days).

To estimate the orbit parameters of the Kepler-9 system we simulated the orbits and the resulting TTV by using a Runge-Kutta integrator, which considers eccentric orbits. Comparing the simulated O-C to the measured O-C shows, that the measured amplitude and beat period is only archived by ether raising the planetary masses or the eccentricity of the orbits (Fig. 4, right). The mass is constrained by the observed radius of the planets which rules out such a high simulated mass, therefore we suppose a slight eccentricity of e=0.07 for the orbit of Kepler-9b. We also started to examine candidates of multi system found by our EXOTRANS pipeline. Fig. 5 demonstrates first results of a system of two candidates detected by transit. The left panel shows the measured TTV's and the best sinus-fit to the data with a beat period of 261 days and an amplitude of 17 minutes. The right panel shows the simulated TTV of this system constrained by the measured periods and the mass calculated from the light curve. The sinus-fit of the simulated data has a beat period of 266 days and an amplitude of 17 minutes. Due to few data points (short beat period) the candidates can not be confirmed by TTV only, but the good agreement between measurement and simulation shows that this candidate should be examined further.
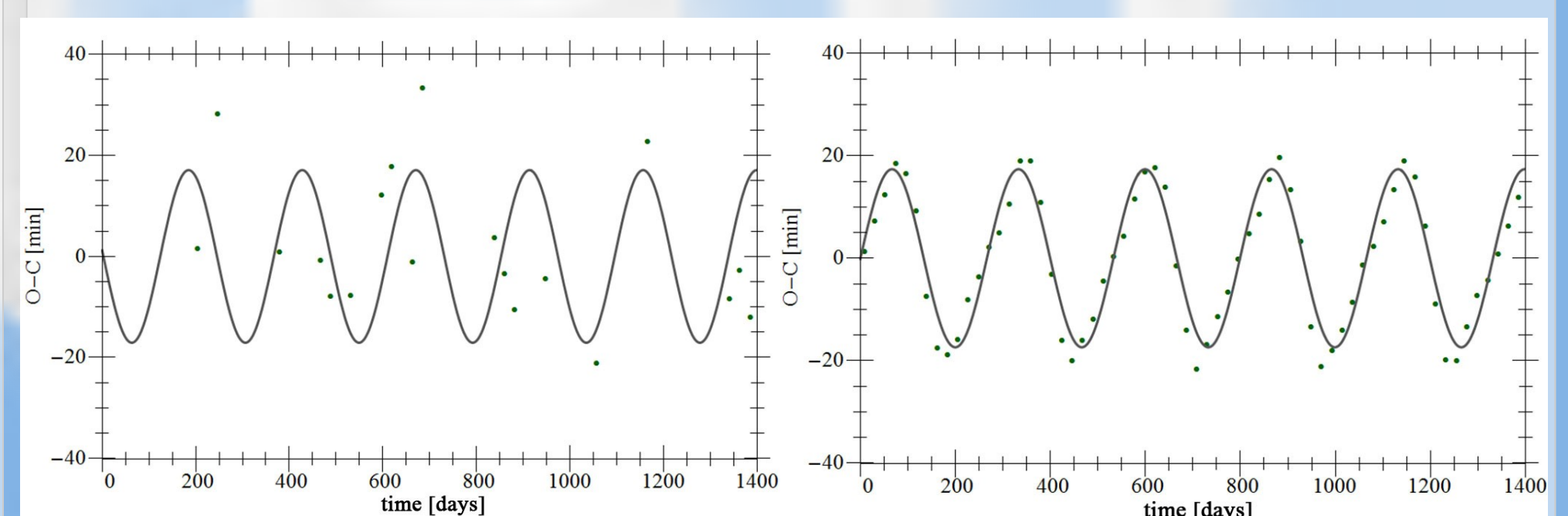

Fig. 5: left: Measured TTV's of a new Kepler candidate found by EXOTRANS. The best sinus fit with a beat period of 261 days is shown.
right: Simulation of the system constrained by the parameters of the transits with a beat period of 266 days an the same amplitude of 17 minutes.

Numerical light curve simulator

The most precise and fastest way to simulate systems of two eclipsing bodies is using a analytic solution to calculate the flux of light curves. This approach is used by the most popular codes like EBOP (Etzel, 1993) or PHOEBE (Prsa and Zwitter, 2005) for simulating eclipsing binaries or planets. The problem becomes more complicated if a third body is included resulting in 27 different cases to calculate (Fewell, 2006). Analytic solution gets impossible if different moons, rings, real star spots (not only circles), or complex star surface structures and star atmospheres have to be simulated. Even if an analytic solution is possible the calculation time raises exponentially. For this reason, the RIU-PF is developing a numerical light curve simulator reducing the problem to a combination of different matrices independent of the number or complexity of the eclipsing bodies . Fig. 6 shows the schematic of the software. A procedural or real texture of a star is mapped on a sphere or ellipsoid. It is also possible to use animated textures. Then the rotation of the body is calculated and the atmosphere of the star (limb darkening) is added. Finally a 2D intensity matrix of the star for the individual time step is calculated. The same procedure can be used for all eclipsing bodies (stars, planets, moons). Afterwards the orbit position for this time step of all eclipsing objects is calculated and projected onto the plain of sight. Finally the matrices are combined and the flux is calculated. Different interpolation methods are used to gain high precision. In the future multiple RGB-matrices for coloured light curves and additional matrices for reflection effects and planetary atmospheres are planned.
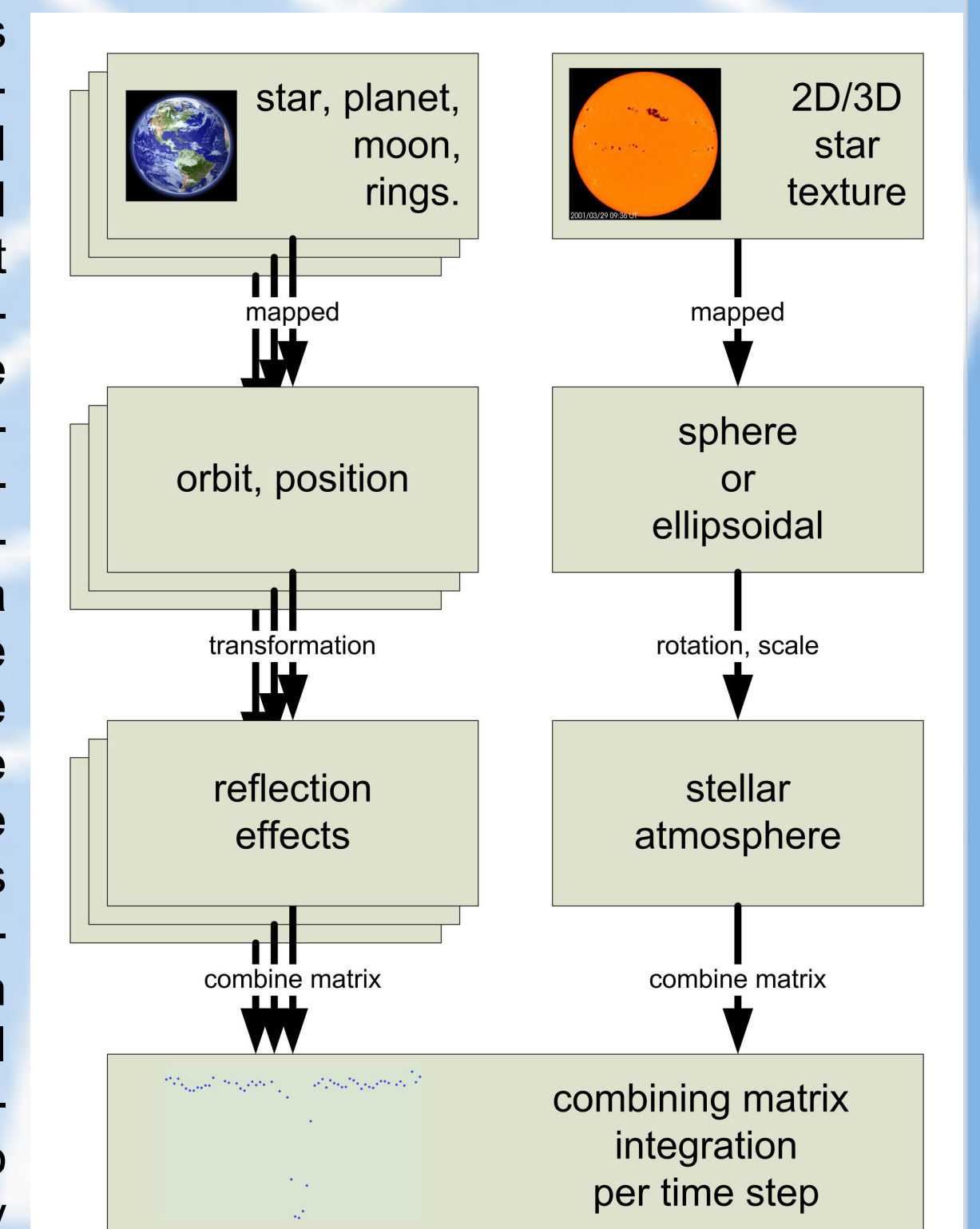

Fig. 6: Schematic view of our new numerical light curve simulator. The numerical concept simplifies the simulation of complex planet, moon systems.

References
Etzel, P. 1993, Current status of the EBOP code. , 1993IAUCB..21..113E
Fewell, M.P. , 2006, Area of common overlap of three circles, DSTO-TN-0722.
Gazak, J. Z., Johnson, J. A. et al. 2012, Transit Analysis Package: An IDL Graphical User Interface for Exoplanet Transit Photometry, Advances in Astronomy, vol. 2012, id. 697967
Grziwa, S.; Pätzold, M., Carone, L. , 2012, The Needle in the haystack, MRAS 420.1045G
Grziwa, S.; Korth, J.; Pätzold, M. , 2011, Detecting planets in Kepler lightcurves using methods developed for CoRoT. , 2011epsc.conf.1409G
Grziwa, S.; Pätzold, M., 2011, Simulation of stellar binary systems: improving the detection of transits in CoRoT lightcurves. 2011epsc.conf.1066G
Holman, M. et al., 2010, Kepler-9: A System of Multiple Planets Transiting a Sun-Like Star, Confirmed by Timing Variations, 10.1126/science.1195778
Mandel, K., Agol, E. 2002, Analytic Light Curves for Planetary Transit Searches , 2002ApJ...580L.171M
Pätzold, M., Endl, M., Csizmadia, Sz., et al. 2012, Transiting exoplanets from the CoRoT space mission. XXIII. CoRoT-21b: a doomed large Jupiter around a faint subgiant star, A&A 545A...6P
Prsa, A, Zwitter, T., 2005, A Computational Guide to Physics of Eclipsing Binaries, 2005ApJ...628..426P
Kov´acs, G., Bakos, G., & Noyes, R. W. 2005, MNRAS, 356, 557