Observations of transit timing variations at the University Observatory Jena

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Abstract

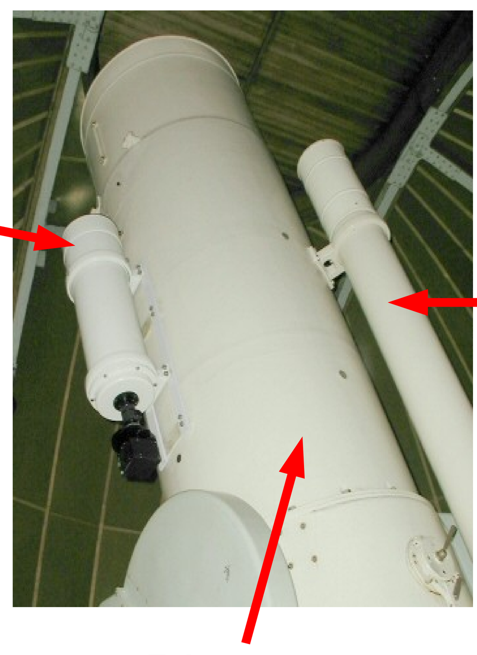
Photometric follow-ups of transiting exoplanets may lead to discoveries of additional, less massive bodies in extrasolar systems. This is possible by detecting and then analyzing variations in transit timing of transiting exoplanets.
In 2009 we launched an international observing campaign to detect and characterize transit timing variation signal in selected transiting exoplanets. The programme is realised by collecting data from 0.6 - 2.2-m telescopes spread worldwide at different longitudes.
Here, we present our observing strategy and summarize first results for selected transiting exoplanets i.e. XO-1b, TrES-1, TrES-2, and WASP-3b.

Since 1962 the Friedrich-Schiller-University Jena operates an observatory. It is about 10 km to the west of Jena on a plateau (close to the small village Großschwabhausen) and offers for its location in Central Europe decent conditions for optical astronomy.

Introduction

The transit event is - in a first approximation - a periodic phenomenon. In a system where a known planet transits its host star, a second planet in that system can cause the time between transits to vary. This technique is itself a planet detection method that is very powerful for searching low-mass planets and is most sensitive for planets in mean-motion resonances. For example, for a hot jupiter (3-day orbit), an Earth mass planet in the 2:1 resonance will cause periodic transit timing variations that have an amplitude greater than one minute (Steffen et al. 2007). It can also be used to detect possible trojans of transiting extrasolar planets (Ford & Holman 2007) or „exomoons“ (Simon et al. 2007).
The transit method is becoming increasingly popular, because even with small telescopes one can achieve great successes. Small ground-based observatories have already exceeded the photometric precision necessary to detect sub-Earth mass planets by the transit timing variation method (Agol et al. 2005).

The Telescopes



View Finder

Focus:	Cassegrain
Diameter:	25 cm
Focal length:	2250 mm
f/D:	9
Instrument:	CCD-Camera CTK

Guide Scope

Focus:	Refractor
Diameter:	20 cm
Focal length:	3000 mm
f/D:	15
Instrument:	CCD-camera RTK

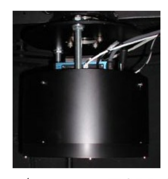
Telescope

Focus:	Schmidt / Nasmyth
Diameter:	60 cm / 90 cm
Focal length:	1800 mm / 13500 mm
f/D:	3 / 15
Instrument:	CCD-camera / spectrograph STK / FIASCO

Cassegrain-Teleskop Kamera

Detector:	SITe TK1024
Pixel:	1024 x 1024
FoV:	37.7' x 37.7'
Filter:	B,V, R, I, z
Focus:	Cassegrain

Schmidt-Teleskop Kamera



Detector:	E2V 42-40
Pixel:	2048 x 2048
FoV:	52.8' x 52.8'
Filter:	B,V, R, I, z
Focus:	Schmidt

Instruments and Observations

We have three telescopes available, a 90 cm reflector, a 20 cm refractor and a 25 cm Cassegrain telescope (see box on the right side).
For our transit observations we use the 25 cm Cassegrain auxiliary telescope equipped with the optical CCD-camera CTK (*Cassegrain Teleskop Kamera*) and our new *Schmidt-Teleskop-Kamera* (STK) installed in summer 2009 in the Schmidt focus of the 90cm telescope.
Our international observing campaign is realised by collecting data from 0.6 - 2.2-m telescopes spread worldwide at different longitudes. Our strategy allows to cover as many as possible transits of our targets.

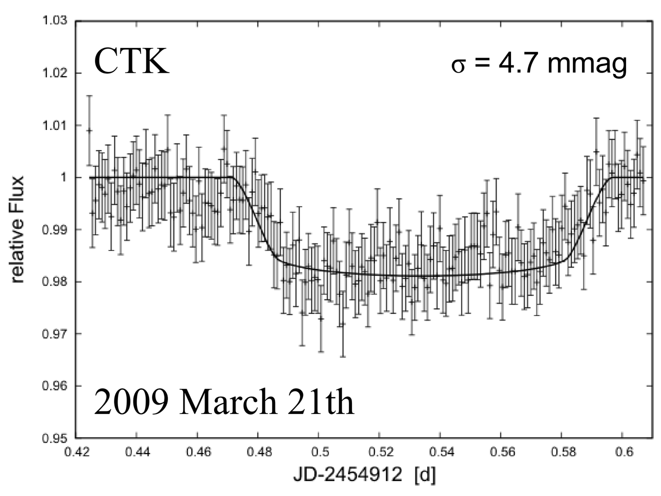
Methods

- Aperture photometry on all available field stars was performed
- A differential photometry algorithm by Broeg et al. (2005) was used to determine the differetial magnitudes.
- An analytic light curve (Mandel & Agol 2002) was applied to fit the data

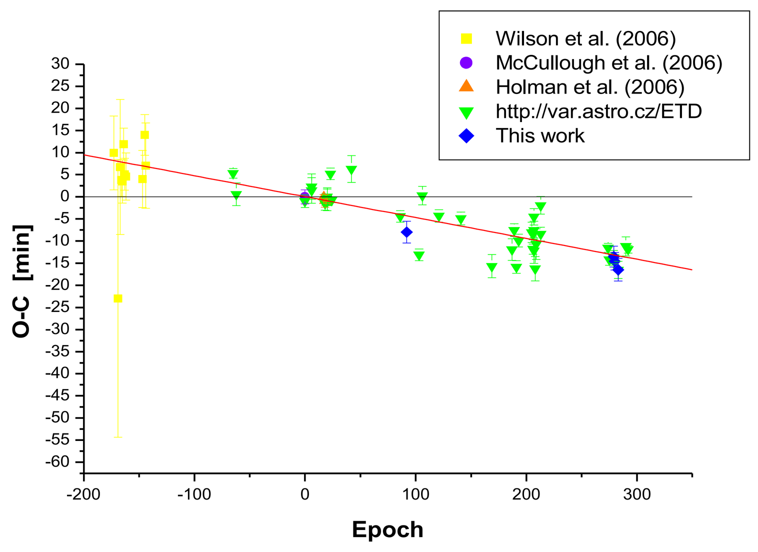
XO-1b, TrES-1 & TrES-2:

Our first efforts to detect TTV signal for the transiting planets XO-1b, TrES-1b and TrES-2b resulted in redetermining their transit ephemerides.

XO-1b:



Relative *I*-band photometry of XO-1 from 2009 March 21/22. The solid line shows the best-fitting model.



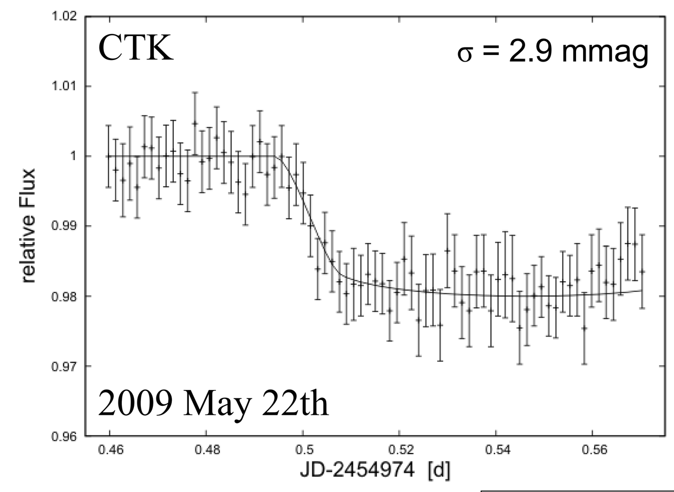
This Figure shows the transit timing residuals for XO-1. The black line shows the ephemeris given by McCullough et al. (2006). The best-fitting line (red line) is plotted, representing the updated ephemeris:

$$T_c(E) = (2453808.91705 + E \cdot 3.941501)\ d$$

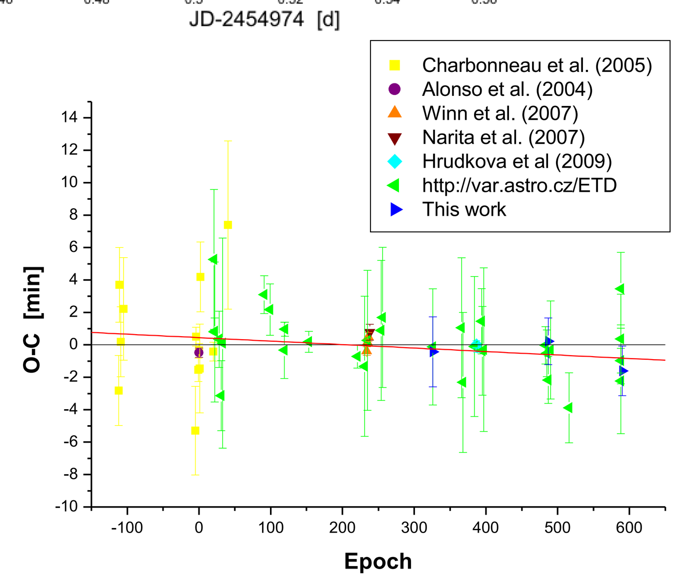
(Raetz et al. 2009b)

TrES-1:

Example of one (partial) light curve of TrES-1. The best-fitting model is again shown as a solid line.



The following figure shows the transit timing residuals for TrES-1. The black and best-fitting (red) line shows the ephemeris given by Winn et al. (2007) and the updated ephemeris, respectively.

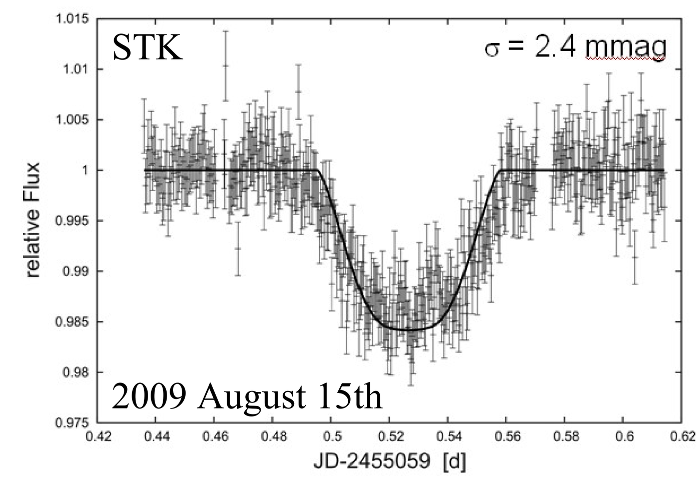


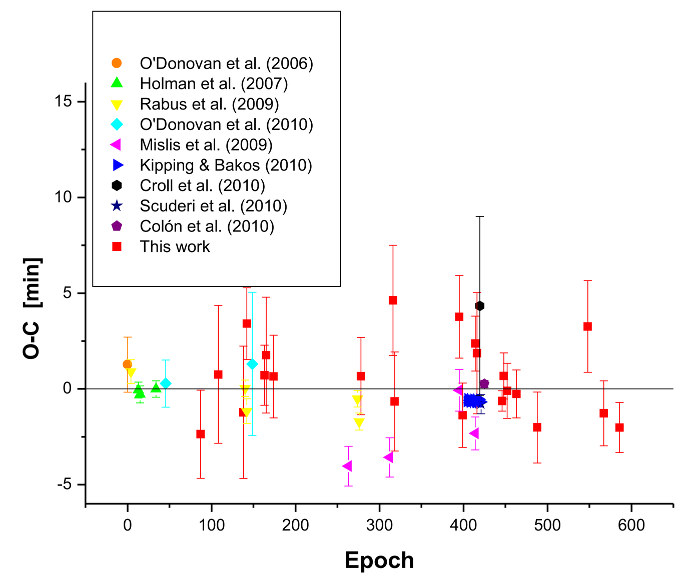
$$T_c(E) = (2453186.806341 + E \cdot 3.0300722)\ d$$

(Raetz et al. 2009b)

TrES-2:

We observed the parent star of the transiting planet TrES-2 over a longer period at the University Observatory Jena. We observed several transit events and almost a complete orbital period.
This figure shows the first transit of TrES-2 observed with STK in summer 2009.





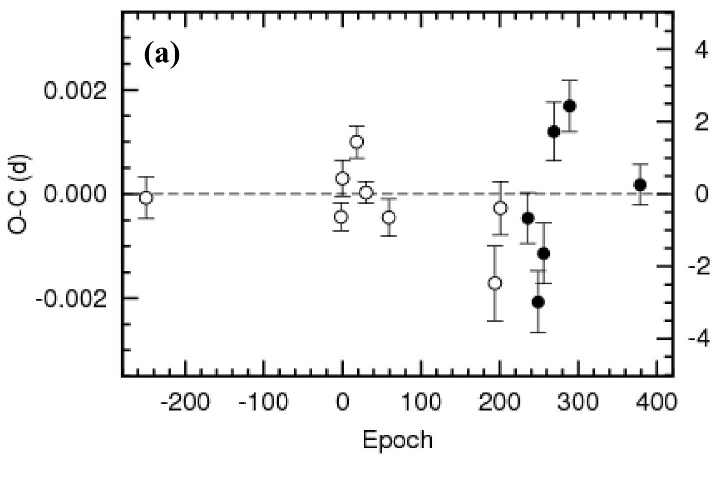
Transit timing residuals for TrES-2. The best-fitting line (black line) is plotted, representing the updated ephemeris:

$$T_c(E) = (2453957.63492 + E \cdot 2.470614)\ d$$

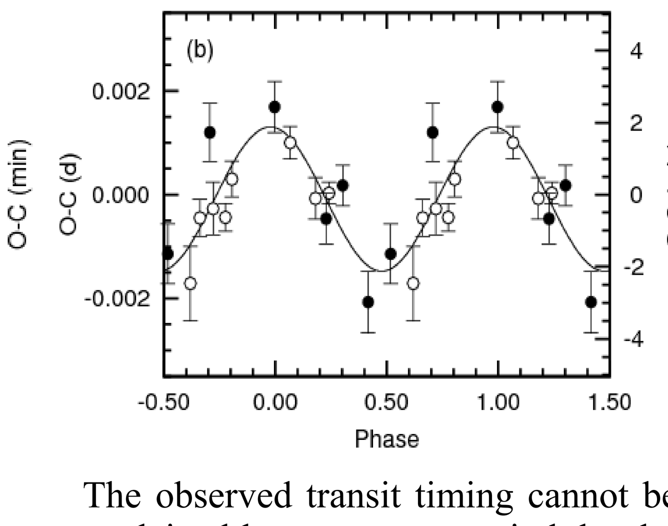
(Raetz et al. 2009a)

WASP-3b:

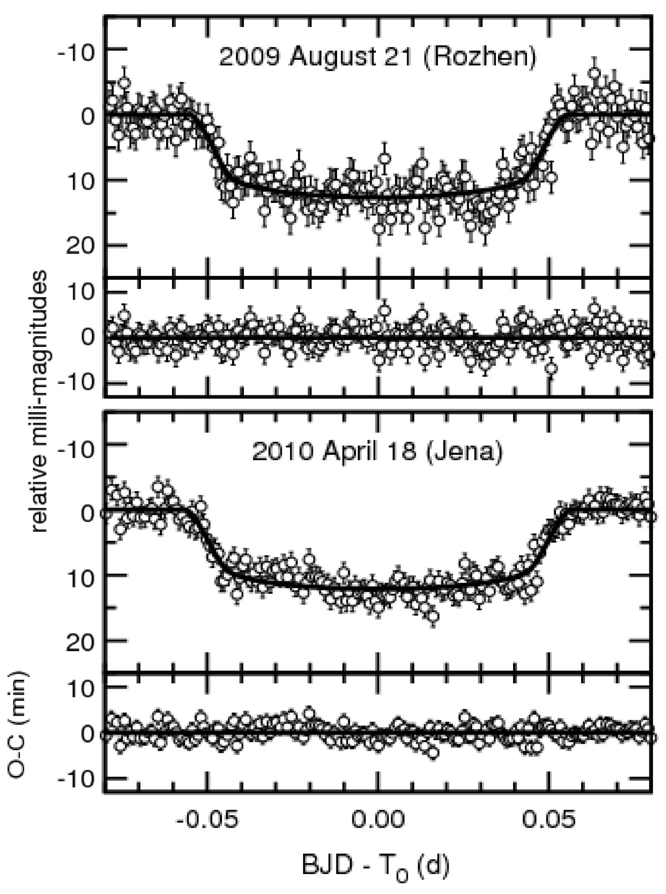
We observed 6 complete transits of WASP-3b with two telescopes both with the effective mirror diameter being 60 cm gathered in 2009 during the dedicated transit-time-variation campaign.
The CCD photometry of 3 transits on 2009 July 28, August 21 and September 3 was gathered with the 60-cm Cassegrain telescope at the Rozhen National Astronomical Observatory (NAO, Bulgaria), operated by the Institute of Astronomy, Bulgarian Academy of Sciences.
Transits on 2009 September 27, November 3 and 2010 April 18 were monitored with the 90-cm reflector telescope at the University Observatory Jena.



The O-C (observed minus calculated) diagram for WASP-3b. The open symbols denote literature data while the filled ones denote results reported in this this work



The observed transit timing cannot be explained by a constant period, but by a periodic variation in the observations allowed to postulate the existence of periodicity in the O-C diagram.



Examples of light curves of WASP-3b transits taken during our campaign. The best-fitting models are shown as continuous lines.

(Maciejewski et al. 2010)

Discussion and Outlook

Our transit timing observations at the University Observatory Jena with a 90 cm reflector and a 25 cm Cassegrain telescope resulted in redetermining the ephemeris of XO-1b, TrES-1 and TrES-2.
We will continue observing known transiting planets to check for timing, and also depth, and duration variation for the next few years to decades.
For WASP-3b, a first example of our international observing campaign, we showed that transit timing cannot be explained by a constant period of the exoplanet. We emphasize that this finding is based on only a few data points.
Simplified models assuming the existence of a perturbing planet in the system and reproducing the observed variations of timing residuals were identified by three-body simulations. We found that the configuration with the hypothetical second planet of the mass of about 15 Earth masses, located close to the outer 2:1 mean motion resonance is the most likely scenario reproducing observed transit timing.
The expected radial-velocity semi-amplitude of the hypothetical second planet would be much smaller than the stellar jitter of WASP-3. This finding reduces chances of a direct detection of the perturber's signal by further radial-velocity follow-ups.
Assuming the hypothetical second planet is also transiting, it would cause periodic flux drops of the host star in the range of 0.03-0.35 per cent (or 0.3-3.8 mmag) depending on the adopted mean planetary density.
As the TTV method requires many high-quality light curves, more data will be gathered for WASP-3b to confirm or disprove the claimed variation in the O-C diagram. A long-time baseline of observations is needed to characterize possible resonant oscillations in the TTV signal. More accurate radial-velocity measurements are also required to gain deeper insight into orbital parameters of the transiting planet. Additionally, a transit of the predicted second planet could be observable with a large ground-based or space-based telescope.