Transit Timing Variations of TrES-2: a combined analysis of ground- and space-based photometry

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Abstract

TrES-2 is one of the few exoplanets, which offer the matchless possibility to combine long-term ground-based observations with continuous satellite data. TrES-2 is a target of our "Transit Timing Variations @ YETI" (TTV@YETI) project which is dedicated to detect and characterize signals of transit timing variations. We observed 43 ground-based light curves of 30 individual transit events of TrES-2. We used seven 0.2 - 2.2m telescopes located at five observatories in Germany and Spain. In addition, we analyzed 16 quarters (Q0-Q15) of observational data from NASA's space telescope *Kepler* including 424 individual transit events. The continuous monitoring of *Kepler* allows to determine the system parameters of each of the 424 transits and search for possible changes of these quantities. Here we present a first indication of an increasing stellar activity of the TrES-2 host star and provide new limits on possible transit timing variations.

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.

Observations

University Observatory Jena: TrES-2 was observed in 27 nights from March 2007 to June 2011. Because of simultaneous observations with up to three telescopes 36 light curves could be obtained.

TTV@YETI: In 2009 we launched an international observing campaign to detect and characterize a TTV signal in selected transiting exoplanets. The program is realized by collecting data from 0.2 - 2.6m telescopes spread worldwide at different longitudes. Our strategy allows to cover as many as possible transits of our targets.
Seven additional transits of TrES-2 were observed by telescopes from TTV@YETI partially parallel to the observations of the University Observatory Jena.

Kepler: For our analysis we downloaded the fully processed ("Presearch Data Conditioning Simple Aperture Photometry", PDCSAP) data from the „NASA Exoplanet Archive".
We analyzed 16 quarters (Q0 to Q15) of *Kepler* data. The light curves cover an overall observation period of May 2nd, 2009 to January 11th, 2013 and included a total of 424 transits of TrES-2 in front of its host star.

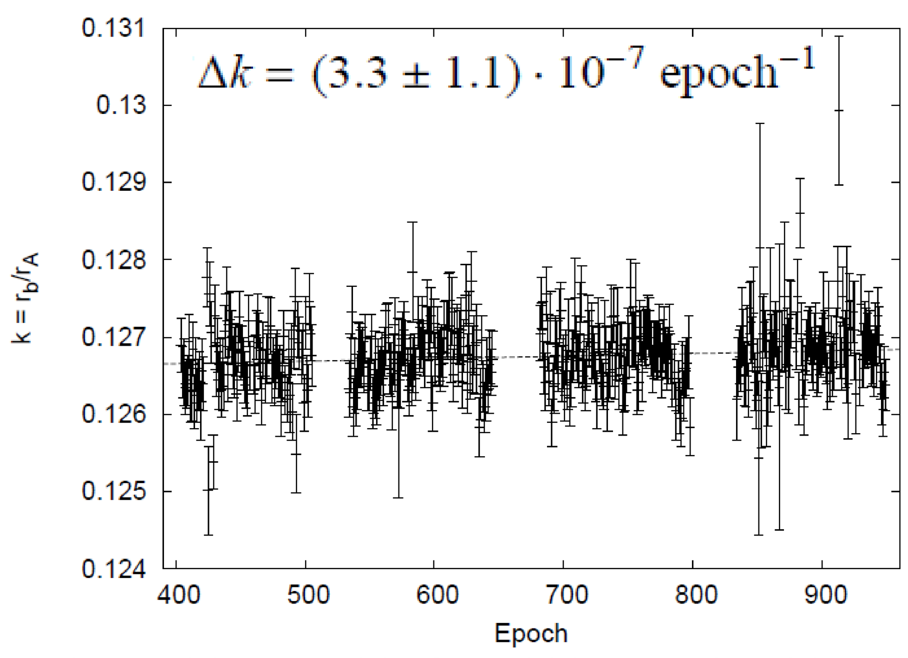
TTV@YETI Telescope network

Methods

- only transits were analyzed that were observed by:
  - University-Observatory Jena
  - TTV@YETI

  ⇒ Data reduction could be carried out uniformly
- Data reduction was done in a standard way for all the participating telescopes
- Magnitudes were derived by aperture photometry
- A differential photometry algorithm by Broeg et al. (2005) was used to determine differetial magnitudes
- The *Kepler* light curves were downloaded completely reduced from the „NASA Exoplanet Archive"
- The JKTEBOP code (Southworth et al. 2004a, 2004b) was used for the light curve modeling

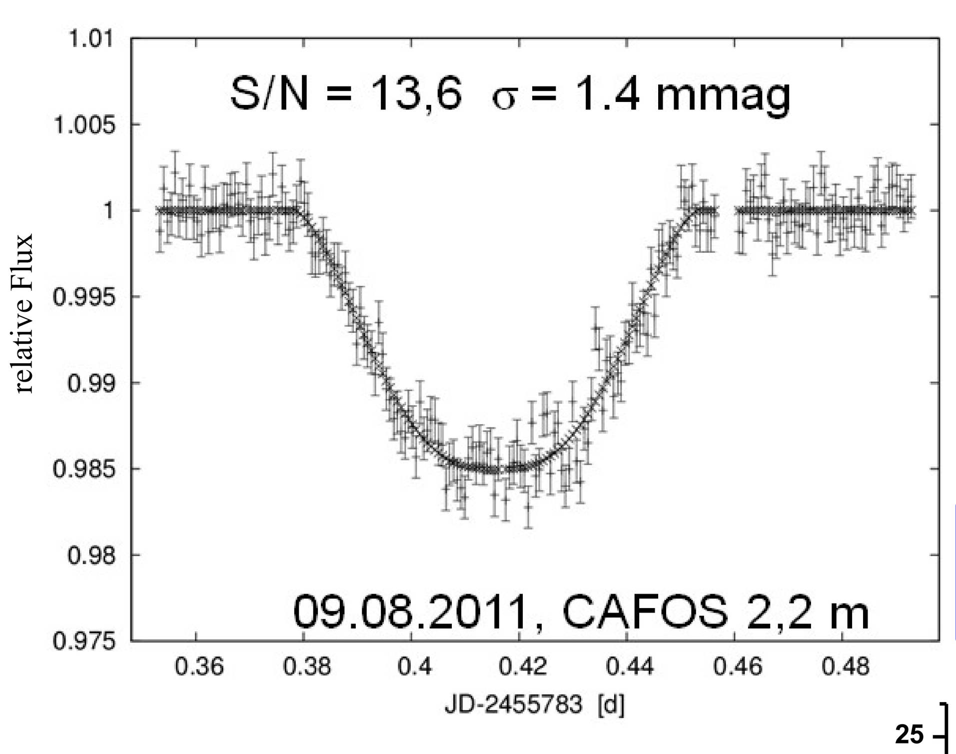
Transit Depth



With the *Kepler* observations it is possible to detect variation of the system parameters.
No deviations were detected for the orbital inclination i and the transit duration D. Only the radius ratio k, hence the transit depth, shows an slight increase (see Figure to the left). This result is significant with 3σ.
A possible explanation could be an increasing stellar activity.

The positive trend in k could be translated into a luminosity decrease of 0.28%. This was transferred into a change of the spot coverage of 0.44%.
The sun shows a change in spot coverage within its cycles of 0.1% (0.34% including Maunder Minimum). Hence, the long-term changes in spot coverage seem to be a plausible explanation for an increasing transit depth.

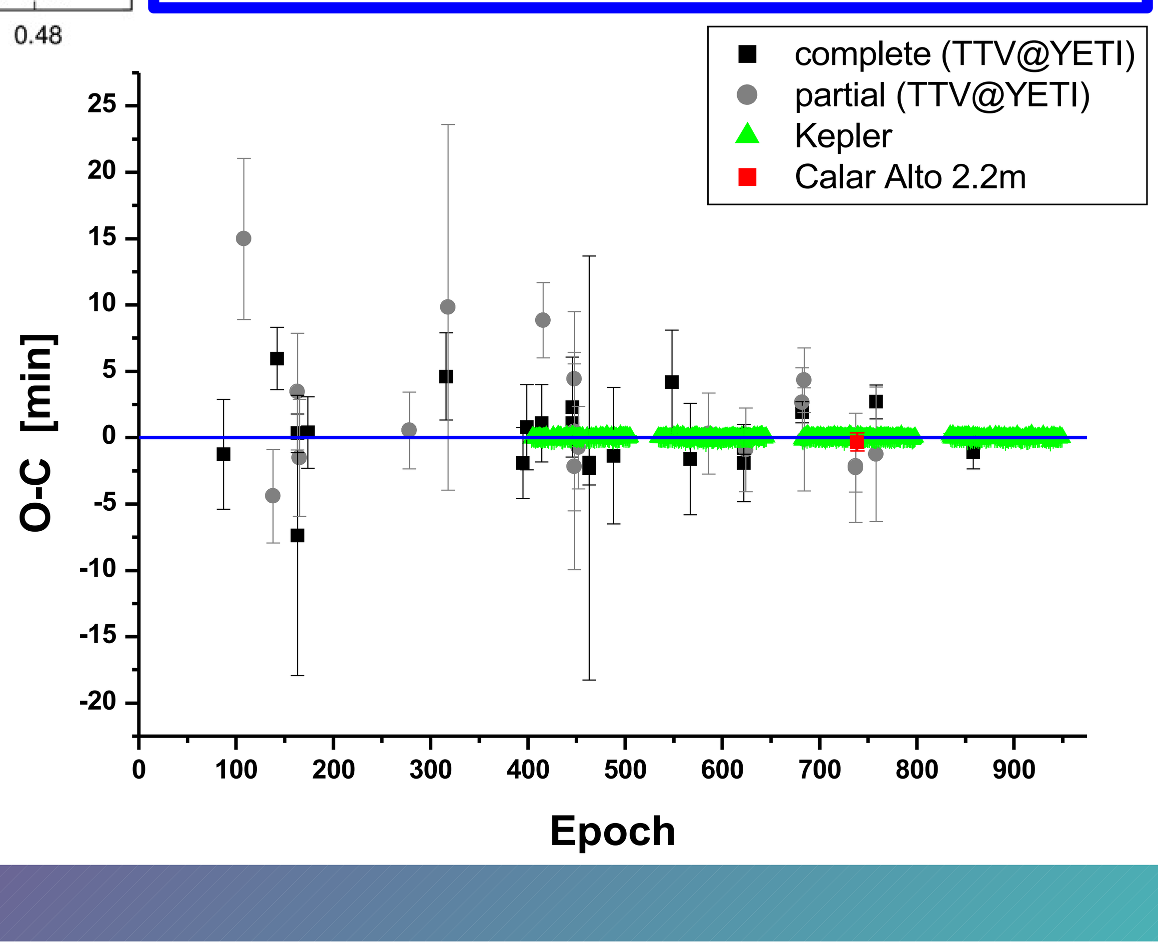
Results



This transit observed with CAFOS at the 2.2m telescope at Calar Alto has the highest S/N of our ground-based observations of TrES-2. The light curve analysis yielded a timing precision of 42s.

Transit timing residuals for all 467 analyzed transit light curves of TrES-2. The blue line shows our refined ephemeris:

$$T_c(E) = (2453957.635496 \pm 0.000011) + E \cdot (2.470613381 \pm 0.000000016)\,\mathrm{d}$$



Both the squares and the circles indicate the transits observed with TTV@YETI. All points shown in gray were observed only partially.
The green triangles mark the 424 *Kepler* transits of 16 quarters.
The red square shows the transit of TrES-2 which was observed at Calar Alto (see above). This point is entirely consistent with the *Kepler* data

→ our error estimations are realistic

Discussion

Subject of this work (Raetz et al. 2013, submitted to A&A) was the search for additional planets in the TrES-2 systems by observation of transit time variations. Since very high quality of the photometry is necessary for the identification of TTVs we paid special attention to the homogeneity of the observation and analysis.
TrES-2 lies in the FoV of the *Kepler* space telescope. Therefore, TrES-2 is one of the few exoplanets, that offer the matchless opportunity to combine long-term ground-based observations with continuous satellite data. The long observation period of seven years (2007-2013) allowed a very precise redetermination of the transit ephemeris.
For a total of 467 transit light curves of TrES-2, the time of transit mid-point was determined. The transit times support neither variations on long nor on short time scales.
The combination of our ground-based data with the *Kepler* observations showed that our transit mid-times and their error bars are reliable i.e. our best data from the Calar Alto 2.2m are very well consistent with the *Kepler* data.
The nearly continuous observations of Kepler show no statistically significant increase or decrease in the orbital inclination i and the transit duration D. Only the transit depth shows a slight increase which could be an indication of an increasing stellar activity. The change in spot coverage of 0.44% seems to be plausible compared to the solar cycle.
In general, system parameters obtained by us were found to be in agreement with previous studies (e.g. Kipping & Bakos 2011, Schröter et al. 2012).