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Ground-based transit observations of the HAT-P-18, HAT-P-19, HAT-P-27/WASP40 and WASP-21 systems

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Accepted 2015 May 22. Received 2015 May 21; in original form 2014 October 7

ABSTRACT
As part of our ongoing effort to investigate transit timing variations (TTVs) of known exoplanets, we monitored transits of the four exoplanets HAT-P-18b, HAT-P-19b, HAT-P-27b/WASP-40b and WASP-21b. All of them are suspected to show TTVs due to the known properties of their host systems based on the respective discovery papers. During the past three years 46 transit observations were carried out, mostly using telescopes of the Young Exoplanet Transit Initiative. The analyses are used to refine the systems’ orbital parameters. In all cases we found no hints for significant TTVs, or changes in the system parameters inclination, fractional stellar radius and planet-to-star radius ratio. However, comparing our results with those available in the literature shows that we can confirm the already published values.

Key words: planets and satellites: individual: HAT-P-18b – planets and satellites: individual: HAT-P-19b – planets and satellites: individual: HAT-P-27b/WASP-40b – planets and satellites: individual: WASP-21b.

1 INTRODUCTION
Observing extrasolar planets transiting their host stars has become an important tool for planet detection and is used to obtain and constrain fundamental system parameters: The inclination has to be close to 90°, while the planet-to-star radius ratio is constrained mainly by the transit depth. Also, in combination with spectroscopy, the semimajor axis and the absolute planet and star radii can be obtained.

Several years ago, when the first results of the Kepler mission were published (see Borucki et al. 2011 for first scientific results and Koch et al. 2010 for an instrument description), studying the transit timing became one of the standard techniques in the analysis of transit observations. Commonly the mid-time of each transit observation is plotted into an observed minus calculated (O–C) diagram (Ford & Holman 2007), where the difference between the observed transit mid-time and the mid-time obtained using the initial ephemeris is shown versus the observing epoch. In such a diagram, remaining slopes indicate a wrong orbital period, while e.g. periodic deviations from a linear trend indicate perturbing forces. Since space-based missions are able to observe many consecutive transit events with high precision, one can detect even small variations of the transit intervals indicating deviations from a strictly Keplerian motion and thus yet hidden planets in the observed system. Furthermore, with the discovery of multiplanetary systems, transit timing variations (TTVs) are used to find the mass of the companions without the need of radial velocity (RV) measurements due to the influence of planetary interaction on TTVs. Since many planet candidates found in photometric surveys are too faint for RV follow-up even with bigger telescopes, TTV analyses can be considered as a photometric workaround to estimate masses.

Although the existence of TTVs can be shown in already known exoplanetary systems, only a few additional planet candidates have
been found using TTVs so far. One of the most prominent examples is the KOI-142 system. By analysing the TTV signals of KOI-142b, Mazeh et al. (2013) suggested the existence of additional planets in the system. Later on, Nesvorný et al. (2013) proposed a non-transiting planet KOI-142c that was confirmed using RV measurements by Barros et al. (2014). Regarding ground-based analyses e.g. Maciejewski et al. (2011a) and von Essen (2013) found indications of TTVs potentially induced by additional planets. The lack of confirmed TTV planets is not surprising, since large bodies often can be found using RV measurements or direct transit detections, while small (e.g. Earth-like) objects result in small TTV amplitudes and therefore high-precision timing measurements are needed. However, these measurements can already be acquired with medium size ground-based telescopes.

Besides the discovery of small planets, the amount of known massive planets on close-in orbits increased as well. First studies on a larger sample of planet candidates detected with Kepler suggest that hot giant planets exist in single planet systems only (Steffen et al. 2011a, 2013b), WASP-3b (Maciejewski et al. 2010, 2013a), WASP-10b (Maciejewski et al. 2011b; Maciejewski et al., in preparation), WASP-14b (Raetz 2012; Raetz et al. 2015), TrES-2 (Raetz et al. 2014) and HAT-P-32b (Seeliger et al. 2014) have been studied in detail. In most cases, except for WASP-12b, no TTVs could be confirmed.

Here, we extend our investigations to search for TTVs in the HAT-P-18, HAT-P-19, HAT-P-27/WASP-40 and WASP-21 planetary systems. In Section 2, we give a short description of the targets analysed within this project. Section 3 explains the principles of data acquisition and gives an overview of the telescopes used for observation. The modelling procedures are described in Section 4, followed by the results in Section 5. Finally, Section 6 gives a summary of our project.

\[\text{Promising candidates among all close-in giant planets discovered so far. Since many of the stars observed with Kepler are too faint to perform RV follow-up, investigating stars outside the field of view (FoV) of Kepler, e.g. objects found by HATnet (Bakos et al. 2004) or the WASP project (Pollacco et al. 2006), is advisable. In our ongoing study of TTVs in exoplanetary systems we perform photometric follow-up observations of specific promising transiting planets where additional bodies are expected. The targets are selected by the following criteria.}\]

(i) There is an indication for a perturber in the system, e.g. a non-zero eccentricity in the orbital solution of the known transiting planet (though the circularization time-scale is much shorter than the system age) or deviant RV data points.

(ii) The brightness of the host star is \( V \leq 13 \) mag and the transit depth is at least 10 mmag to ensure sufficient photometric and timing precision at 1–2 m class ground-based telescopes.

(iii) The target is visible from the Northern hemisphere.

(iv) The target has not been studied for TTV signals before.

In the past the transiting exoplanets WASP-12b (Maciejewski et al. 2011a, 2013b), WASP-3b (Maciejewski et al. 2010, 2013a), WASP-10b (Maciejewski et al. 2011b; Maciejewski et al., in preparation), WASP-14b (Raetz 2012; Raetz et al. 2015), TrES-2 (Raetz et al. 2014) and HAT-P-32b (Seeliger et al. 2014) have been studied by our group in detail. In most cases, except for WASP-12b, no TTVs could be confirmed.

\[\text{1 see http://ttv.astri.umk.pl/doku.php for a project overview.}\]
# Date Telescope Filter Exposures

**HAT-P-18b**

1* 2011-04-21 Trebur 1.2 m $R_B$ 189 $\times$ 90 s
2 2011-05-02 Trebur 1.2 m $R_B$ 123 $\times$ 45 s
3* 2011-05-24 Trebur 1.2 m $R_B$ 323 $\times$ 60 s
4 2011-06-04 Rozhen 2.0 m $R_C$ 1000 $\times$ 10 s
5* 2012-05-05 Rozhen 0.6 m $R_C$ 219 $\times$ 90 s
6 2012-06-07 CA DLR 1.23 m $R_1$ 250 $\times$ 60 s
7 2013-04-28 Antalya 1.0 m $R$ 214 $\times$ 50 s
8 2014-03-30 Toruń 0.6 m Clear 297 $\times$ 40 s

**HAT-P-19b**

9* 2011-11-23 Jena 0.6 m $R_B$ 246 $\times$ 50 s
10 2011-11-23 Jena 0.25 m $R_B$ 320 $\times$ 50 s
11 2011-11-23 Trebur 1.2 m $R_B$ 461 $\times$ 30 s
12 2012-12-05 Jena 0.6 m $R_B$ 129 $\times$ 60 s
13* 2012-12-05 Jena 0.25 m $R_B$ 28 $\times$ 300 s
14* 2012-12-09 Jena 0.6 m $R_B$ 290 $\times$ 50 s
15 2011-12-09 Jena 0.25 m $V_B$ 118 $\times$ 150 s
16 2011-12-09 Trebur 1.2 m $R_B$ 380 $\times$ 35 s
17* 2011-12-17 CA DLR 1.23 m $R_1$ 273 $\times$ 60 s
18 2014-08-01 Antalya 1.0 m $R$ 148 $\times$ 60 s
19 2014-08-05 Antalya 1.0 m $R$ 196 $\times$ 40 s
20 2014-08-21 Jena 0.6 m $R_B$ 152 $\times$ 50 s
21* 2014-10-04 Jena 0.6 m $R_B$ 280 $\times$ 50 s

**HAT-P-27b**

22* 2011-04-05 Lulin 0.4 m $R_B$ 166 $\times$ 40 s
23* 2011-04-08 Lulin 0.4 m $R_B$ 250 $\times$ 40 s
24 2011-05-03 Stella 1.2 m $H_\alpha$ 180 $\times$ 100 s
25* 2011-05-05 Trebur 1.2 m $R_B$ 162 $\times$ 70 s
26 2011-05-08 Stella 1.2 m $H_\alpha$ 190 $\times$ 100 s
27 2011-05-21 Tenagra 0.8 m $R$ 141 $\times$ 40 s
28 2012-03-07 StaraLesna 0.5 m $R$ 361 $\times$ 30 s
29 2012-03-29 Tenagra 0.8 m $R$ 240 $\times$ 30 s
30 2012-04-01 Tenagra 0.8 m $R$ 329 $\times$ 20 s
31 2012-04-04 Tenagra 0.8 m $R$ 333 $\times$ 20 s
32 2012-04-25 Xinglong 0.6 m $R$ 154 $\times$ 40 s
33 2012-05-16 Trebur 1.2 m $R_B$ 231 $\times$ 70 s
34 2012-05-25 Chile 0.15 m $K_2(R_1)$ 220 $\times$ 80 s
35 2012-06-13 Tenagra 0.8 m $R$ 223 $\times$ 15 s
36* 2013-06-03 Antalya 1.0 m $R$ 156 $\times$ 60 s
37* 2013-06-03 OSN 1.5 m $R$ 435 $\times$ 30 s
38 2013-06-06 CA DLR 1.23 m $R_1$ 172 $\times$ 60 s
39* 2014-06-18 Antalya 1.0 m $R$ 146 $\times$ 50 s

**WASP-21b**

40* 2011-08-24 Swarthmore 0.6 m $R_B$ 545 $\times$ 45 s
41 2011-08-24 Gettysburg 0.4 m $R_B$ 230 $\times$ 60 s
42* 2012-08-16 Trebur 1.2 m $R_B$ 365 $\times$ 40 s
43 2012-10-20 Antalya 1.0 m $R$ 242 $\times$ 40 s
44* 2013-09-18 CA DLR 1.23 m $R_1$ 584 $\times$ 30 s
45 2013-09-22 Antalya 1.0 m $R$ 208 $\times$ 50 s
46 2013-09-22 Ulupinar 0.6 m $R_B$ 163 $\times$ 110 s

## 2 TARGETS

### 2.1 HAT-P-18b and HAT-P-19b

Hartman et al. (2011) reported on the discovery of the exoplanets HAT-P-18b and HAT-P-19b. The two Saturn-mass planets orbit their early K-type host stars with periods of 5.51 and 4.01 d, respectively.

In the case of HAT-P-18b, Hartman et al. (2011) found the eccentricity to be slightly non-zero ($e = 0.084 \pm 0.048$). Recent studies of Esposito et al. (2014) found the eccentricity to be consistent with a non-eccentric retrograde orbit by analysing the Rossiter–McLaughlin effect. Knutson et al. (2014) also analysed the RV signal and found a jitter of the order of 17.5 m s$^{-1}$ that remains unexplained. Ginski et al. (2012) presented the results of the lucky imaging campaign with AstraLux at the Calar Alto 2.2 m Telescope to search for additional low-mass stellar companions in the system. With the data gathered in this previous study objects down to a mass of 0.140 $\pm$ 0.022 M$_\odot$ at angular separations as small as 0.5 arcsec and objects down to 0.099 $\pm$ 0.008 M$_\odot$ outside of 2 arcsec could already be excluded. In addition to this study, we performed follow-up observations of HAT-P-18b planetary transits, as well as a monitoring project of the planet host star over a longer time span to possibly find overall brightness variations.

For HAT-P-19b, a small eccentricity of $e = 0.067 \pm 0.042$ was determined by Hartman et al. (2011). They also found a linear trend in the RV residuals pointing towards the existence of a long-period perturber in the system. Within this project we want to address the problem of the proposed perturber using photometric methods, i.e. follow-up transit events to find planetary induced TTV signals.

### 2.2 HAT-P-27b/WASP-40b

HAT-P-27b (Béky et al. 2011), independently discovered as WASP-40b by Anderson et al. (2011) within the WASP-survey (Pollacco et al. 2006), is a typical hot Jupiter with a period of 3.04 d. While the eccentricity was found to be $e = 0.078 \pm 0.047$ by Béky et al. (2011), Anderson et al. (2011) adopted a non-eccentric orbit. However, the latter authors found a huge spread in the RV data with up to 40 m s$^{-1}$ deviation from the circular single planet solution. According to Anderson et al. (2011) one possible explanation, despite a changing activity of the K-type host star, is the existence of a perturber that might not be seen in the Béky et al. (2011) data due to the limited data set. However, the authors suggest further monitoring to clarify the nature of the system. One possibility is to study the companion hypothesis from the TTV point of view.

Another interesting aspect is the transit shape of HAT-P-27b. With an increasing impact parameter $b = a/R$, the typical flat bottom phase of the box-shaped transit becomes shorter and even vanished completely for grazing transit events (V-shaped transit). The data of Béky et al. (2011) show a flat bottom phase, while the best-fitting solutions of Anderson et al. (2011) and Sada et al. (2012) point towards a V-shape. The latter ones found that there is a high probability that the system is grazing using the grazing criterion (Smalley et al. 2011). Though this would explain the unusual shape of the transit, the impact parameter of the U-shaped transit seen by Béky et al. (2011) ($b = 0.89$) lies between the one derived by Anderson et al. (2011) and Sada et al. (2012) ($b = 0.86$ and $b = 0.92$, respectively). New high-quality observations of HAT-P-27b planetary transits could be used to further constrain the real system configuration.
Table 3. The input parameters for the JKTEBOP and TAP runs for all objects listed in Section 2. All values have been obtained from the original discovery papers. LD coefficients are taken from Claret & Bloemen (2011) linear interpolated in terms of $T_{\text{eff, log} g}$ and [Fe/H] using the EXOFAST/QUADLD code (Eastman et al. 2013). Free parameters are marked by an asterisk. At the bottom the duration of ingress and egress according to Winn (2010) has been added.

<table>
<thead>
<tr>
<th>Object</th>
<th>HAT-P-18b</th>
<th>HAT-P-19b</th>
<th>HAT-P-27b</th>
<th>WASP-21b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_p + r_s^*$</td>
<td>0.0575(19)</td>
<td>0.0709(33)</td>
<td>0.1159(65)</td>
<td>0.0959(44)</td>
</tr>
<tr>
<td>$R_p/R_s^*$</td>
<td>0.1365(15)</td>
<td>0.1418(20)</td>
<td>0.1186(31)</td>
<td>0.1040(35)</td>
</tr>
<tr>
<td>$i^*$</td>
<td>88.8(3)</td>
<td>88.2(4)</td>
<td>84.7(7)</td>
<td>88.75(84)</td>
</tr>
<tr>
<td>$a/R_s^*$</td>
<td>16.04(75)</td>
<td>12.24(67)</td>
<td>9.65(54)</td>
<td>10.54(48)</td>
</tr>
<tr>
<td>$M_p/M_s$</td>
<td>0.000 243(26)</td>
<td>0.000 229(37)</td>
<td>0.000 663(58)</td>
<td>0.000 282(19)</td>
</tr>
<tr>
<td>$e$</td>
<td>0.084(48)</td>
<td>0.067(42)</td>
<td>0.078(47)</td>
<td>0.0</td>
</tr>
<tr>
<td>$P$ (d)</td>
<td>5.508 0023(06)</td>
<td>4.008 778(06)</td>
<td>3.039 586(12)</td>
<td>4.322 482(24)</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ (K)</td>
<td>4803(80)</td>
<td>4990(130)</td>
<td>5300(90)</td>
<td>5800(100)</td>
</tr>
<tr>
<td>$\log g$ (cgs)</td>
<td>4.57(04)</td>
<td>4.54(05)</td>
<td>4.51(04)</td>
<td>4.51(04)</td>
</tr>
<tr>
<td>[Fe/H] (dex)</td>
<td>$+0.10(08)$</td>
<td>$+0.23(08)$</td>
<td>$+0.29(10)$</td>
<td>$-0.46(11)$</td>
</tr>
<tr>
<td>$v\sin i$ (km s$^{-1}$)</td>
<td>0.5(5)</td>
<td>0.7(5)</td>
<td>0.4(4)</td>
<td>1.5(6)</td>
</tr>
</tbody>
</table>

LD law of the star

- $R$ band linear* Quadratic Quadratic Quadratic Quadratic
- $R$ band non-linear* 0.5736 0.5433 0.4808 0.3228
- $V$ band linear* 0.1474 0.1710 0.2128 0.2982
- $V$ band non-linear* 0.7180 0.6783 0.6002 0.4055
- $\tau_{\text{egress/ingress}}$ (min) 0.0697 0.1039 0.1643 0.2892
- $\tau_{\text{egress}}$ (min) 22.8 23.1 37.8 20.1

2.3 WASP-21b

The planetary host star WASP-21, with its Saturn-mass planet on a 4.32 d orbit discovered by Bouchy et al. (2010), is one of the most metal-poor planet hosts accompanied by one of the least dense planets discovered by ground-based transit searches to date. Bouchy et al. (2010) found that including a small non-zero eccentricity to the fit does not improve the results. Hence, they concluded that the eccentricity is consistent with zero.

In a later study, Barros et al. (2011) found the G3V star to be in the process of moving off the main sequence. Hence, though the WASP-21 system does not match our criteria concerning the expectations for additional bodies in the system, we included further observations of WASP-21b planetary transits to improve the knowledge on this system.

3 DATA ACQUISITION AND REDUCTION

Our observations make use of YETI network telescopes (Young Exoplanet Transit Initiative; Neuhäuser et al. 2011), a worldwide network of small- to medium-size telescopes mostly on the Northern hemisphere established to explore transiting planets in young open clusters.

A summary of all participating telescopes and the number of performed observations can be found in Table 1. Most of the observing telescopes are part of the YETI network. This includes telescopes at Cerro Armazones (Chile, operated by the University of Bochum), Gettysburg (USA), Jena (Germany), Lulin (Taiwan), Rozhen (Bulgaria), Sierra Nevada (Spain), Stará Lesná (Slovak Republic), Swarthmore (USA), Tenagra (USA, operated by the National Central University of Taiwan) and Xinglong (China). For details about location, mirror and chip, see Neuhäuser et al. (2011).

In addition to the contribution of the YETI telescopes, we obtained data using the following telescopes:

(i) the 1.2 m telescope of the German–Spanish Astronomical Center on Calar Alto (Spain), which is operated by German Aerospace Center (DLR);

(ii) the 1.2 m robotic telescope STELLA-I, situated at Teide Observatory on Tenerife (Spain) and operated by the Leibnitz-Institut für Astrophysik Potsdam;

(iii) the Trebur 1 Meter Telescope operated at the Michael Adrian Observatory Trebur (Germany);

(iv) the T100 telescope of the TÜBITAK National Observatory (Turkey);

(v) the 0.6 m telescope (CIST60) at Ulunpar Observatory operated by Istanbul University (Turkey);

(vi) the 0.6 m Cassegrain telescope of the Toruń Centre for Astronomy (Poland).

Besides the transit observations, the Jena 0.6 m telescope with its Schmidt Teleskop Kamera (Mugrauer & Berthold 2010) was used to perform a long term monitoring of HAT-P-18 as described in Sections 2.1 and 5.1.
Between 2011 April and 2013 June our group observed 46 transit events (see Table 2) using 18 different telescopes (see Table 1). 16 observations could be used for further analysis, while 30 observations had to be rejected due to several reasons, e.g. no full transit event has been observed or bad weather conditions and hence low signal to noise. For example, Southworth et al. (2009a, 2009b) showed that defocusing the telescope allows us to reduce flat fielding effects. Since the light of a star is spread over a larger amount of pixels and more light is gathered due to a longer exposure time, seeing effects are reduced as well as photon noise. Since a defocused image spreads the light over several CCD pixel, one can increase the exposure time and hence the effective duty cycle of the CCD assuming a constant read out time (as mentioned also in the conclusions of Barros et al. 2011). Thus we tried to defocus the telescope and increase the exposure time during all our observations. Table 3 lists the ingress/egress durations t derived using the formulas (18) and (19) given in Winn (2010). With our strategy we obtain at least one data point within 90 s. This ensures to have at least 10 data points during ingress/egress phase which is required to fit the transit model to the data and get precise transit mid-times.

All data have been reduced in a standard way by applying dark/bias and flat-field corrections using IRAF. The respective calibration images have been obtained in the same night and

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2 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
with the same focus as the scientific observations. This is necessary especially if the pointing of the telescope is not stable. When using calibration images obtained with different foci, patterns remain in the images that lead to distortions in the light curve.

Besides our own observations, we also use literature data. This involves data from the respective discovery papers mentioned in Section 2, as well as data from Esposito et al. (2014) in the case of HAT-P-18b, Sada et al. (2012) in the case of HAT-P-27b, Barros et al. (2011) and Ciceri et al. (2013) for WASP-21b, and Simpson et al. (2010) for WASP-38b.

4 ANALYSES

The light-curve extraction and modelling is performed analogous to the procedure described in detail in Seeliger et al. (2014).
4.1 Light-curve extraction

The Julian date of each image is calculated from the header information of the start of the exposure and the exposure time. To precisely determine the mid-time of the transit event, these pieces of information have to be stored most accurate. The reliability of the final light-curve model thus also depends on a precise time synchronization of the telescope computer system. Since all data are obtained using JDU TC as time base, we transform the fitted mid-transit times to BJD TDB afterwards using the online converter\footnote{3 \url{http://astroutils.astronomy.ohio-state.edu/time/utc2bjd.html}} provided by

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Top: the transit light curves obtained for HAT-P-27b. Bottom: the present result for the HAT-P-27b observing campaign. All explanations are equal to Fig. 2. The open circles denote data from the discovery papers of Béky et al. (2011) and Anderson et al. (2011), open triangles denote literature data from Sada et al. (2012) and Brown et al. (2012) (the latter one set to epoch 200 artificially), filled triangles denote our data (from Lulin, Trebur, Xinglong and Antalya).}
\end{figure}
Table 4. Impact parameters of HAT-P-27b planetary transits.

<table>
<thead>
<tr>
<th>Observation epoch</th>
<th>Impact parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>155 – Lulin 0.4 m</td>
<td>0.84 ± 0.30</td>
</tr>
<tr>
<td>156 – Lulin 0.4 m</td>
<td>0.87 ± 0.23</td>
</tr>
<tr>
<td>165 – Trebur 1.2 m</td>
<td>0.84 ± 0.12</td>
</tr>
<tr>
<td>415 – Antalya 1.0 m</td>
<td>0.81 ± 0.27</td>
</tr>
<tr>
<td>415 – OSN 1.5 m</td>
<td>0.85 ± 0.06</td>
</tr>
<tr>
<td>540 – Antalya 1.0 m</td>
<td>0.89 ± 0.19</td>
</tr>
<tr>
<td>Our analysis combined</td>
<td>0.859 ± 0.023</td>
</tr>
<tr>
<td>Beky et al. (2011)</td>
<td>0.89 ± 0.17</td>
</tr>
<tr>
<td>Anderson et al. (2011)</td>
<td>0.86 ± 0.07</td>
</tr>
<tr>
<td>Sada et al. (2012)</td>
<td>0.92 ± 0.24</td>
</tr>
<tr>
<td>Brown et al. (2012)</td>
<td>0.85 ± 0.07</td>
</tr>
</tbody>
</table>

Jason Eastman (for a detailed description of the barycentric dynamical time see Eastman, Siverd & Gaudi 2010).

We use differential aperture photometry to extract the light curve from the reduced images by measuring the brightness of all bright stars in the field with routines provided by IRAF. The typical aperture radius is ≈1.5 times the mean full width half-maximum of all stars in the FoV. The best-fitting aperture is found by manually varying the aperture radius by a few pixels to minimize the photometric scatter. The final light curve is created by comparing the star of interest through the FoV. The best-fitting aperture is found by manually varying the aperture radius by a few pixels to minimize the photometric scatter. The final light curve is created by comparing the star of interest against an artificial standard star composed of the (typically 15–30) brightest stars in the FoV weighted by their respective constantness as introduced by Broeg, Fernández & Neuhäuser (2005).

The final photometric errors are based on the instrumental IRAF measurement errors. The error of the constant comparison stars are rescaled by their photometric scatter using shared scaling factors in order to achieve a mean $\chi^2_{red} \approx 1$ for all comparison stars. The error bars of the transit star are rescaled afterwards using the same scaling factors (for further details on the procedure, see Broeg et al. 2005).

Trends in light curves induced by atmospheric effects can impact the determination of transit parameters. To eliminate such effects we start the observation about 1 h before and finish about 1 h after the transit itself. Thus we can detrend the observations by fitting a second-order polynomial to the out-of-transit data.

4.2 Modelling with TAP and JKTEBOP

To model the light curves we used the Transit Analysis Package (TAP, version v2.104; Gazak et al. 2012). The modelling of the transit light curve is done by using the EXOFAST routine (Eastman, Gaudi & Agol 2013) with the light-curve model of Mandel & Agol (2002). For error estimation TAP uses Markov Chain Monte Carlo simulations (in our case 10 times $10^5$ MCMC chains) together with wavelet-based likelihood functions (Carter & Winn 2009). The coefficients for the quadratic limb-darkening (LD) law used by TAP are taken from the EXOFAST/QUADLD-routine of Eastman et al. (2013)4 that linearly interpolates the LD tables of Claret & Bloemen (2001).

For comparison we also use JKTEBOP (version 25, see Southworth 2008, and references therein) which is based on the EBOP code for eclipsing binaries (Etzel 1981; Popper & Etzel 1981). To compare the results with those obtained with TAP, we only use a quadratic LD law which is sufficient for ground-based data. For error estimation we used Monte Carlo simulations (task #7, $10^3$ runs), bootstrapping (task #8, $10^4$ data sets) and a residual shift method (task #9) as provided by JKTEBOP.

As input values for the modelling we take the system properties presented in the respective discovery papers (see Table 3 for a summary). As free parameters we use the mid-transit time $T_{mid}$, inclination $i$, and planet-to-star radius ratio $k = r_p/r_s$ (with $r_p$ and $r_s$ being the planet and stellar radius scaled by the semimajor axis, respectively). In the case of TAP, the inverse fractional stellar radius $a/R_s = 1/r_s$, in the case of JKTEBOP the sum of the fractional radii ($r_p + r_s$) is fitted as well. Both quantities are an expression of the transit duration and can be transformed into each other according to the following equation:

$$a/R_s = \left(1 + r_p/r_s\right) / \left(r_p + r_s\right).$$

The fitting procedure is applied two times. First, keeping the LD coefficients fixed at their theoretical values, and afterwards letting them vary. For TAP we set the fitting interval to ±0.2. In the case of JKTEBOP, we use the option to set the LD coefficients fixed for the initial model, but let them being perturbed for the error estimation. Thus the fitted model does not change, but the error bars are increased. The eccentricity was fixed to zero for all our analyses.

Finally, we derive the photometric noise rate (pnr; Fulton et al. 2011) as a quality marker for all light curves, which is defined as the ratio between the root mean square of the model fit and the number of data points per minute. For further analysis, we took data with pnr ≤ 4.5 into account which corresponds to a timing precision of $\Delta T_{mid} \approx 90$ s.

5 RESULTS

For every light curve, we get three different models, two from TAP (for the model with the LD coefficients fixed and free, respectively) and one from JKTEBOP (LD coefficients set free for error estimation only). To get one final result for every transit event, we averaged those three results. As for the errors, we got two different estimations from TAP and six from JKTEBOP. As final error value, we took the maximum of either the largest of the error estimates, or the spread of the model fit results to use a conservative error estimate. It has to be noted, though, that the spread between the different models has always been below size of the error bars.

The same counts for the differences between the TAP models obtained with fixed LD values and those obtained with the LD coefficients set free to fit. For a detailed discussion of the influence of the LD model on transit light curves, see e.g. Raetz et al. (2014).

The redetermination of the system parameters is performed with ORIGIN 6.0 (OriginLab, Northampton, MA). In order to find possible deviations from a constant value, we use the internally provided linear fitting function with a fixed slope of zero on all single results obtained for a given target and property. The individual model errors are taken as instrumental weights during the $\chi^2$-minimization fitting procedure.

5.1 HAT-P-18b

Over a timespan of 12 months, we observed three images in four bands ($B$, $V$, $R$, $I$) in each clear night using the Jena 0.6 m telescope in order to look at the long-term variability of the parent star. As shown in Fig. 1, the mean variation of the $R$-band brightness is ≈0.9 mmag taking the individual error bar of the measurements into account. The result is in agreement with no variation.
Looking at the Exoplanet Transit Database (ETD; Poddaňy, Bráť & Pejcha 2010) one can see that the values for the transit depth reported there vary by several tens of mmag. Such variations can be caused by close variable stellar companions placed within the aperture due to the pixel scale of the detectors and the telescope defocusing. However, our results together with the data of Hartman et al. (2011) and Esposito et al. (2014) neither show a variation in the transit depth, i.e. the $k$-value, nor the overall stellar brightness. Thus, the data provided by ETD in the case of HAT-P-27b should be treated with caution.

For HAT-P-18b, we obtained three useful transit observations (see Fig. 2). However, due to the size of the used telescopes, the relatively faint planet host star and the small amount of suitable comparison stars available in the respective FoV of each observation, the resultant light curves are dominated by a large scatter.

Except for one – but not significant – outlier the differences in the O–C diagram (see Fig. 2) can be explained by redetermining the published period by $(0.53 \pm 0.36)$ s. Hence, our result is in good agreement with the originally published period of Hartman et al. (2011).

Despite a spread in the data, which can be explained by the quality of the light curves, we do not see any significant differences for $k$, $i$ and $R/R_e$ between the respective observations. A summary of all obtained parameters can be found in Table 5, as well as a comparison with literature values.

### 5.2 HAT-P-19b

For HAT-P-19b, we got two light curves using the Jena 0.6 m and one light curve from the CAHA 1.2 m telescope (Fig. 3). In all three cases, we obtained high-precision data. The light curves show no artefacts that could be ascribed to e.g. spots on the stellar surface. Plotting the mid-transit times into the O–C diagram, we can determine the period by $(0.53 \pm 0.06)$ s. As for the inclination and the reverse fractional stellar radius, we can confirm the values reported in Hartman et al. (2011). The radius ratio of $k = 0.1378 \pm 0.0014$, however, seems to be smaller than assumed by Hartman et al. (2011) ($k = 0.1418 \pm 0.0020$).

### 5.3 HAT-P-27b

HAT-P-27b planetary transits were observed six times (see Fig. 4). Unfortunately, due to the observing conditions and sizes of the telescopes used for the observations most light curves are of lower quality. An advantage of a network such as the YETI network lies within the possibility of simultaneous observations using different telescopes. This enables us to independently check whether the data are reliable. For HAT-P-27b, simultaneous observations could be achieved at epoch 415 using two different telescopes (Antalya 1.0 m and OSN 1.5 m).

In addition to our own data, we added data from Sada et al. (2012) and Brown et al. (2012). The latter one only lists system parameters without giving an epoch of observation, thus we artificially put them to epoch 200. The system parameters $i$, $R/R_e$ and $k$ can be determined more precisely than before taking the errors of the individual measurements into account. All three parameters are in good agreement with the results of previous authors. Furthermore, we do not see any significant variation. The larger $k$-value of the epoch 540 observations are due to the quality of the corresponding light curve.

Looking at the mid-transit time we see that a period change of $(0.51 \pm 0.12)$ s explains the data quite well. The mid-transit time of one of the epoch 415 observations was found to be $\approx 4.5$ min ahead of time, while the other one is as predicted. This way we could identify a synchronization error during one of the observations. This example shows the importance of simultaneous transit observations. Unfortunately, this was the only successful observation of that kind within this project (for a larger set of double and threefold observations, see e.g. Seeliger et al. 2014).

As mentioned before, one of the previous discussions in the case of HAT-P-27b planetary transits has been the transit shape. Table 4 lists the derived impact parameters for our single observations,
Figure 5. Top: the transit light curves obtained for WASP-21b. Bottom: the present result for the WASP-21b observing campaign. All explanations are equal to Fig. 2. The open circle denotes data from the discovery paper of Bouchy et al. (2010), open triangles denote literature data from Barros et al. (2011), Ciceri et al. (2013) and Southworth (2012) (the latter one artificially set to epoch 200), filled triangles denote our data (from Swarthmore, Trebur and Calar Alto).

as well as the weighted mean and the literature results. Though there are small deviations between the different transit events, no significant difference can be seen. Our observations point towards $b = 0.86$ and thus confirm the results of Anderson et al. (2011) and Békéy et al. (2011). One has to state, though, that the error bars of the individual results are quite large. With $b > 0.8$ the HAT-P-27 system shows one of the largest known impact parameter of all known transiting exoplanets in combination with a very high probability that the transit is indeed gracing.

5.4 WASP-21b

Four transit light curves of WASP-21b are available, including one light curve from Barros et al. (2011) (see Fig. 5). In addition,
During the past three years we followed these well-chosen objects medium-size telescopes with the help of YETI network telescopes. We presented the results of the transit observations of the extra-solar planets HAT-P-18b, HAT-P-19b, HAT-P-27b/W ASP-40b and HAT-P-40b. Table 5 contains an overview of the redetermined properties, as well as the available literature values, while Table 6 lists the results of the individual light-curve fits.

In all cases we could redetermine the orbital parameters. Especially, the period could be determined more precise than before. So far, we cannot rule out the existence of TTV signals for the planets investigated within this study due to the limited number of available high-quality data. Also the parameters \( a/R_s, r_p/R_s \) and inclination have been obtained and compared to the available literature data. Despite some corrections to the literature data, we found no significant variations within these parameters. To distinguish between a real astrophysical source of the remaining scatter and random noise as a result of the quality of our data more high-precision transit observations would be needed.

HAT-P-18b was also part of an out-of-transit monitoring for a spread in the transit depth was reported in the literature that could be due to a significant variability of the transit host star. Regarding our transit data we cannot confirm the spread in transit depth. Looking at the quality of the literature data showing the transit depth variation, it is very likely that this spread is of artificial nature. Thus it is not surprising that we did not find stellar variability larger than \( \pm 3.8 \) mmag. However, we do see some structures in the light curves that could be caused by spot activity on the stellar surface.

### ACKNOWLEDGEMENTS

All the participating observatories appreciate the logistic and financial support of their institutions and in particular their technical workshops. MS would like to thank the DFG for support in the Collaborative Research Center Sonderforschungsbereich SFB TR 7 ‘Gravitationswellenastronomie’. RE, MK, SR and RN would like to thank the DFG for support in the Priority Programme SPP 1385 on the First ten Million years of the Solar system in projects NE 515/34-1 and -2. RN would like to...
acknowledge financial support from the Thuringian government (B 515-07010) for the STK CCD camera (Jena 0.6 m) used in this project. MM and CG thank DFG in project MU 2695/13-1. The research of DD and DK was supported partly by funds of projects DO 02-362, DO 02-85 and DDVU 0240/2010 of the Bulgarian Scientific Foundation, as well as project RD-08-261 of Shumen University. Z-YU was supported by the Chinese National Natural Science Foundation grant no. 11373033. The research of RC, MH is supported as a project of the Nordrhein-Westfälische Akademie der Wissenschaften und Künste in the framework of the academy programme by the Federal Republic of Germany and the state Nordrhein-Westfalen. MF acknowledges financial support from grants AYA2011-30147-C03-01 of the Spanish Ministry of Economy and Competitiveness (MINECO), cofunded with EU FEDER funds, and 2011 FQM 7363 of the Consejería de Economía, Innovación, Ciencia y Empleo (Junta de Andalucía, Spain). We also wish to thank the TUBITAK National Observatory (TUG) for supporting this work through project numbers 12BT100-324-0 and 12CT100-388 using the T100 telescope. MS thanks D. Keeley, M. M. Hohle and H. Gilbert for supporting the observations at the University Observatory Jena. This research has made use of NASA’s Astrophysics Data System. This research is based on observations obtained with telescopes of the University Observatory Jena, which is operated by the Astrophysical Institute of the Friedrich-Schiller-University. This work has been supported in part by Istanbul University under project number 39742, by a VEGA Grant 2014/14 of the Slovak Academy of Sciences and by the joint fund of Astronomy of the National Science Foundation of China and the Chinese Academy of Science under grants U1231113.

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