

AperTO - Archivio Istituzionale Open Access dell'Università di Torino

**TOI-2046b, TOI-1181b and TOI-1516b, three new hot Jupiters from TESS: planets orbiting a young star, a subgiant and a normal star**

**This is the author's manuscript**

*Original Citation:*

*Availability:*

This version is available <http://hdl.handle.net/2318/1948612> since 2023-12-21T07:43:06Z

*Published version:*

DOI:10.1093/mnras/stac1254

*Terms of use:*

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)

# TOI-2046b, TOI-1181b and TOI-1516b, three new hot Jupiters from *TESS*: planets orbiting a young star, a subgiant and a normal star

Petr Kabáth,<sup>1\*</sup> Priyanka Chaturvedi,<sup>2</sup> Phillip J. MacQueen,<sup>3</sup> Marek Skarka,<sup>1</sup> Ján Šubjak,<sup>1,4</sup> Massimiliano Esposito,<sup>2</sup> William D. Cochran,<sup>9</sup> Salvatore E. Bellomo,<sup>11</sup> Raine Karjalainen,<sup>1</sup> Eike W. Guenther,<sup>2</sup> Michael Endl,<sup>10</sup> Szilárd Csizmadia,<sup>5</sup> Marie Karjalainen,<sup>1</sup> Artie Hatzes,<sup>2</sup> Jiří Žák,<sup>6</sup> Davide Gandolfi,<sup>11</sup> Henri M.J. Boffin,<sup>6</sup> Jose I. Vines,<sup>7</sup> John H. Livingston,<sup>8</sup> Rafael A. García<sup>35</sup> Savita Mathur<sup>12,13</sup> Lucía González-Cuesta<sup>12,13</sup> Martin Blažek,<sup>1,21</sup> Douglas A. Caldwell,<sup>23</sup> Knicole D. Colón,<sup>24</sup> Hans Deeg,<sup>12,13</sup> Anders Erikson,<sup>5</sup> Vincent Van Eylen,<sup>15</sup> William Fong,<sup>26</sup> Malcolm Fridlund,<sup>16,17</sup> Akihiko Fukui,<sup>29,12</sup> Gábor Fűrész,<sup>26</sup> Robert F. Goeke,<sup>25</sup> Elisa Goffo,<sup>11,2</sup> Steve Howell,<sup>22</sup> Jon M. Jenkins,<sup>22</sup> Peter Klagyivik,<sup>5</sup> Judith Korth,<sup>18</sup> David W. Latham,<sup>18</sup> Rafael Luque,<sup>27</sup> Dan Moldovan,<sup>28</sup> Felipe Murgas,<sup>12</sup> Norio Narita,<sup>29,30,31,12</sup> Jaume Orell-Miquel,<sup>12,13</sup> Enric Palle,<sup>12,13</sup> Hannu Parviainen,<sup>12,13</sup> Carina M. Persson,<sup>16</sup> Phillip A. Reed,<sup>14</sup> Seth Redfield,<sup>19</sup> George R. Ricker,<sup>25</sup> Sara Seager,<sup>26,33,34</sup> Luisa Maria Serrano,<sup>11</sup> Avi Shporer,<sup>26</sup> Alexis M. S. Smith,<sup>5</sup> Noriharu Watanabe,<sup>32</sup> Joshua N. Winn,<sup>20</sup> and the KESPRINT team

<sup>1</sup>Astronomical Institute of the Czech Academy of Sciences, Fričova 298, 25165, Ondřejov, Czech Republic

<sup>2</sup>Thüringer Landessternwarte Tautenburg, Sternwarte 5, 07778 Tautenburg, Germany

<sup>3</sup>McDonald Observatory, The University of Texas at Austin, Austin, TX 78712, USA

<sup>4</sup>Astronomical Institute of Charles University, V Holešovičkách 2, 180 00, Prague, Czech Republic

<sup>5</sup>Department of Extrasolar Planets and Atmospheres, German Aerospace Center, Rutherfordstrasse 2., D-12489 Berlin, Germany

<sup>6</sup>European Southern Observatory, Karl-Schwarzschild-Str. 2., D-85748 Garching bei Muenchen, Germany

<sup>7</sup>Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile

<sup>8</sup>Department of Astronomy, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

<sup>9</sup>Center for Planetary Systems Habitability and McDonald Observatory, The University of Texas, Austin, TX 78712, USA

<sup>10</sup>Center for Planetary Systems Habitability and Department of Astronomy, The University of Texas, Austin, TX 78712, USA

<sup>11</sup>Dipartimento di Fisica, Università Degli Studi di Torino Via Pietro Giuria, 1, 10125 Torino

<sup>12</sup>Instituto de Astrofísica de Canarias (IAC), 38205 La Laguna, Tenerife, Spain

<sup>13</sup>Departamento de Astrofísica, Universidad de La Laguna (ULL), 38206 La Laguna, Tenerife, Spain

<sup>14</sup>Department of Physical Sciences, Kutztown University, Kutztown, PA, 19530, USA

<sup>15</sup>Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, UK

<sup>16</sup>Chalmers University of Technology, Department of Space, Earth and Environment, Onsala Space Observatory, SE-439 92 Onsala, Sweden

<sup>17</sup>Leiden Observatory, University of Leiden, PO Box 9513, 2300 RA, Leiden, The Netherlands

<sup>18</sup>Department of Space, Earth and Environment, Astronomy and Plasma Physics, Chalmers University of Technology, 412 96 Gothenburg, Sweden

<sup>19</sup>Astronomy Department and Van Vleck Observatory, Wesleyan University, Middletown, CT 06459, USA

<sup>20</sup>Department of Astrophysical Sciences, Peyton Hall, 4 Ivy Lane, Princeton, NJ 08544, USA

<sup>21</sup>Department of Theoretical Physics and Astrophysics, Faculty of Science, Masaryk University, Kotlářská 267/2, 611 37 Brno, Czech Republic

<sup>22</sup>NASA Ames Research Center, Moffett Field, CA 94035, USA

<sup>23</sup>SETI Institute, 189 Bernardo Ave, Suite 200 Mountain View, CA 94043, USA

<sup>24</sup>NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

<sup>25</sup>Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

<sup>26</sup>Department of Physics and Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

<sup>27</sup>Instituto de Astrofísica de Andalucía (IAA-CSIC), Glorieta de la Astronomía s/n, 18008 Granada, Spain

<sup>28</sup>Google, Cambridge, MA, USA

<sup>29</sup>Komaba Institute for Science, The University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan

<sup>30</sup>Japan Science and Technology Agency, PRESTO, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan

<sup>31</sup>Astrobiology Center, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

<sup>32</sup>Department of Multi-Disciplinary Sciences, Graduate School of Arts and Sciences, The University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan

<sup>33</sup>Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

<sup>34</sup>Department of Aeronautics and Astronautics, MIT, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

<sup>35</sup>Laboratoire AIM, CEA/DSM – CNRS – Université Paris Diderot – IRFU/SAp, 91191 Gif-sur-Yvette Cedex, France

Accepted XXX. Received YYY; in original form ZZZ

**ABSTRACT**

We present the confirmation and characterization of three hot Jupiters, TOI-1181b, TOI-1516b, and TOI-2046b, discovered by the TESS space mission. The reported hot Jupiters have orbital periods between 1.4 and 2.05 days. The masses of the three planets are  $1.18 \pm 0.14 M_J$ ,  $3.16 \pm 0.12 M_J$ , and  $2.30 \pm 0.28 M_J$ , for TOI-1181b, TOI-1516b, and TOI-2046b, respectively. The stellar host of TOI-1181b is a F9IV star, whereas TOI-1516b and TOI-2046b orbit F main sequence host stars. The ages of the first two systems are in the range of 2-5 Gyrs. However, TOI-2046 is among the few youngest known planetary systems hosting a hot Jupiter, with an age estimate of 100-400 Myrs. The main instruments used for the radial velocity follow-up of these three planets are located at Ondřejov, Tautenburg and McDonald Observatory, and all three are mounted on 2-3 meter aperture telescopes, demonstrating that mid-aperture telescope networks can play a substantial role in the follow-up of gas giants discovered by *TESS* and in the future by *PLATO*.

**Key words:** techniques: spectroscopic – techniques: radial velocities – planets and satellites: detection – stars: individual: TOI-1181, TOI-1516, TOI-2046

**1 INTRODUCTION**

Hot Jupiters are planets with a mass and radius similar to Jupiter while orbiting their host star in less than about 10 days. Due to their short proximity to their stellar host, hot Jupiters belong to an extremely puzzling group of planets from the evolutionary point of view. Already the first hot Jupiter ever discovered, 51 Peg b, raised the question of the formation and evolution of such systems (Mayor & Queloz 1995). Immediately, some classical theories of gas planet formation were challenged (Pollack et al. 1996).

In spite of over 25 years of studies of hot Jupiters, there are at least two very good reasons to continue such work:

- 1) insights into planet formation
- 2) atmospheric characterization

Although hot Jupiters were the first exoplanets to be discovered, this is an observational bias due to their short orbital periods and large sizes. Exoplanet surveys later showed that the occurrence rate of hot Jupiters is about 0.43% (Masuda & Winn 2017) – less than the 5.2% fraction of Jupiter-sized planets on longer orbits and significantly lower than the occurrence rates of smaller planets (Fressin et al. 2013). However, the occurrence rate of giant planets differs also based on the metallicity of the host star, with metal-rich stars being more likely to host a giant planet (Wang et al. 2015).

It is still not clear whether hot Jupiters formed in-situ (Batygin et al. 2016) or if they formed far away from their host star and migrated inwards (Heller 2019). Furthermore, systems with several Jupiter-sized planets such as HR 8799 are most likely very rare (Wright et al. 2009; Marois et al. 2008). This particular system, HR 8799, is also an example of a young exoplanetary system of an age of a few hundreds of millions of years (Song et al. 2001). Only a handful of such young systems are known. The youngest fully characterized gas giant in terms of mass and radius is the recently discovered *TESS* planet, HIP 67522 b, of about one Jupiter mass with an age of  $17 \pm 2$  Myrs (Rizzuto et al. 2020). Young hot Jupiters are important objects for understanding the evolution of exoplanetary systems as well as the formation history of systems with smaller planets (Weiss et al. 2017; Huang et al. 2020c).

Hot Jupiters are also interesting targets for investigating exo-

atmospheres, as the atmospheric signatures of large gas planets can be detected even with mid-sized aperture telescopes from the ground (Wytenbach et al. 2015; Žák et al. 2019). In some cases, the atmospheres of hot Jupiters might be extended and extremely hot (Yan et al. 2021; Cauley et al. 2021). Nevertheless, atmospheric processes in hot Jupiters are now being understood at a rapid pace and new models are calculated to understand the composition of atmospheres of giant planets (Gao et al. 2020).

Finally, one should also mention here the aspect of telescope time optimization during the ground-based follow-up of exoplanetary candidates. Hot Jupiters are indeed ideal targets for mid-aperture telescopes equipped with precise spectrographs. Such instruments are capable of performing the necessary confirmation and in some cases, even allow their characterization. Mid-aperture class telescopes are ideal instruments to exclude false positives for transit detections. The typical global rate of false positives in the *Kepler* sample is about 6 – 7%, up to 17% for giant planets only (Fressin et al. 2013). The *TESS* mission global false positives rate is about 25% (Guerrero et al. 2021). Therefore, the confirmation of transit candidates requires many hours of telescope time.

In this paper, we report the confirmation of the *TESS* discovery of three gas giant planets on short orbits. Planetary candidates TOI-1516b, TOI-1181b and TOI-2046b were confirmed via a coordinated radial-velocity (RV) follow-up monitoring at the Ondřejov 2m Perek telescope (Kabáth et al. 2020), at the Alfred Jensch 2m telescope in Tautenburg (Hatzes et al. 2003), and at the 2.7m telescope at McDonald Observatory (Tull et al. 1995), as part of a joint KESPRINT effort.

The KESPRINT<sup>1</sup> consortium has been a major contributor for the characterization of gas planets (Smith et al. 2019; Johnson et al. 2018; Barragán et al. 2018; Hjorth et al. 2019; Eigmüller et al. 2017; Smith et al. 2017; Grziwa et al. 2016; Johnson et al. 2016) found by the *K2* mission (Howell et al. 2014), and currently also for small planets (Gandolfi et al. 2019; Esposito et al. 2019; Luque et al. 2021; Fridlund et al. 2020; Carleo et al. 2020; Bluhm et al. 2020; Van Eylen et al. 2021) found by the *TESS* mission (Ricker et al. 2015). Besides small planets, KESPRINT also led the characterization of the first transiting brown dwarf found by *TESS*, TOI-503b (Šubjak et al. 2020).

\* E-mail: petr.kabath@asu.cas.cz

<sup>1</sup> <http://kesprint.science>

## 2 OBSERVATIONAL DATA SETS

Here, and in the following section, we describe the data flow process from the *TESS* discovery light curves up to the RV follow-up observations.

### 2.1 *TESS* light curves

*TESS* is a mission designed to detect exoplanets from space, using the transit method (Ricker et al. 2014). The spacecraft consists of four identical cameras with four  $2k \times 2k$  CCDs monitoring a field-of-view of  $24^\circ \times 24^\circ$ . The mission covers about 85% of the sky. Until July 2020, *TESS* recorded every 2 minutes the flux of over 200,000 main-sequence stars. *TESS* also obtained full-frame images (FFIs) of the entire, four camera field-of-view at a cadence of 30 minutes. The hot Jupiters reported in this article were observed during the northern hemisphere monitoring campaign in 2019 and 2020. All three systems were identified by the *TESS* Quick Look Pipeline (QLP; Huang et al. 2020a,b).

*TESS* observed TOI-1181 in sectors 14, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25 and 26 and 40 and an alert was issued by the *TESS* Science Office on 27 August 2019 (Guerrero et al. 2021). The resulting Data Validation reports (Twicken et al. 2018; Li et al. 2019) are exceptionally clean and the difference image centroiding locates the source of the transit signatures to within 2.5 arcsec. There are no nearby stars in the *TESS* Input Catalog (TIC) sufficiently bright to explain the transit signature as a background eclipsing binary.

TOI-1516 was observed in sectors 17, 18, 24 and 25 and an alert was issued on 5 December 2019, while TOI-2046 was observed in sectors 18, 19, 24 and 25 and an alert issued on 19 June 2019. The cutoff images with each target were extracted from the *TESS* Target-Pixel-Files (TPF) with the default optimum aperture using the *LIGHTKURVE* v 2.0 package (Lightcurve Collaboration et al. 2018). The images are shown in the left-hand panels of Figure 1. In order to inspect initially the *TESS* light curves of the three systems, we used again *LIGHTKURVE* 2.0 with the data downloaded from the MAST archive<sup>2</sup>.

We show the light curves of the three systems obtained with the Simple Aperture Photometry (SAP) pipeline by the Science Processing Operations Center (SPOC) (Jenkins et al. 2016; Twicken et al. 2010; Morris et al. 2020) in the right-hand side of Figure 1. The full analysis with our noise model description is presented in 3.1.

Catalogue parameters describing the three systems including *TESS*, optical and IR magnitudes and coordinates are summarized in Table 1.

### 2.2 Ground-based photometric follow-up

In this section, we describe the ground-based photometric follow-up to check for potential contamination and confirm transit on target. All the presented data were used for a joint fit with the *TESS* data and with the spectroscopic data sets.

#### 2.2.1 The Carlson R. Chambliss Astronomical Observatory (CRCAO)

The Carlson R. Chambliss Astronomical Observatory (CRCAO) is located on the campus of Kutztown University in Pennsylvania and operates a fork-mounted 0.6 m Ritchey–Chrétien optical telescope with a focal ratio of f/8. The imaging CCD (KAF-6303E) camera has an array of  $3k \times 2k$  ( $9 \mu m$ ) pixels and the system covers a field of view of  $19.5' \times 13.0'$ . The CCD is cooled to  $-30^\circ C$ . With  $2 \times 2$  binning, the pixel scale is 0.76" and the telescope is auto-guided with a total drift of less than 10 pixels throughout an entire night of continuous observations. Seeing at CRCAO is typically about 3".

CRCAO observed a full transit of TOI-1181 b on UT 2019 September 25, with 311 consecutive 60 s exposures in the  $R_C$  band. However, the observing sequence was interrupted due to a technical problem between fractions of BJD 0.7-0.8, as presented at the top of Figure A1. CRCAO also observed a full transit of TOI-1516 b on 2020 August 10, with 205 consecutive 90 s exposures in the  $R_C$  band. Both data sets were detrended with airmass. The light curve is shown at the bottom of Figure reflscrcao.

#### 2.2.2 MUSCAT2 Observations at the Carlos Sanchez Telescope

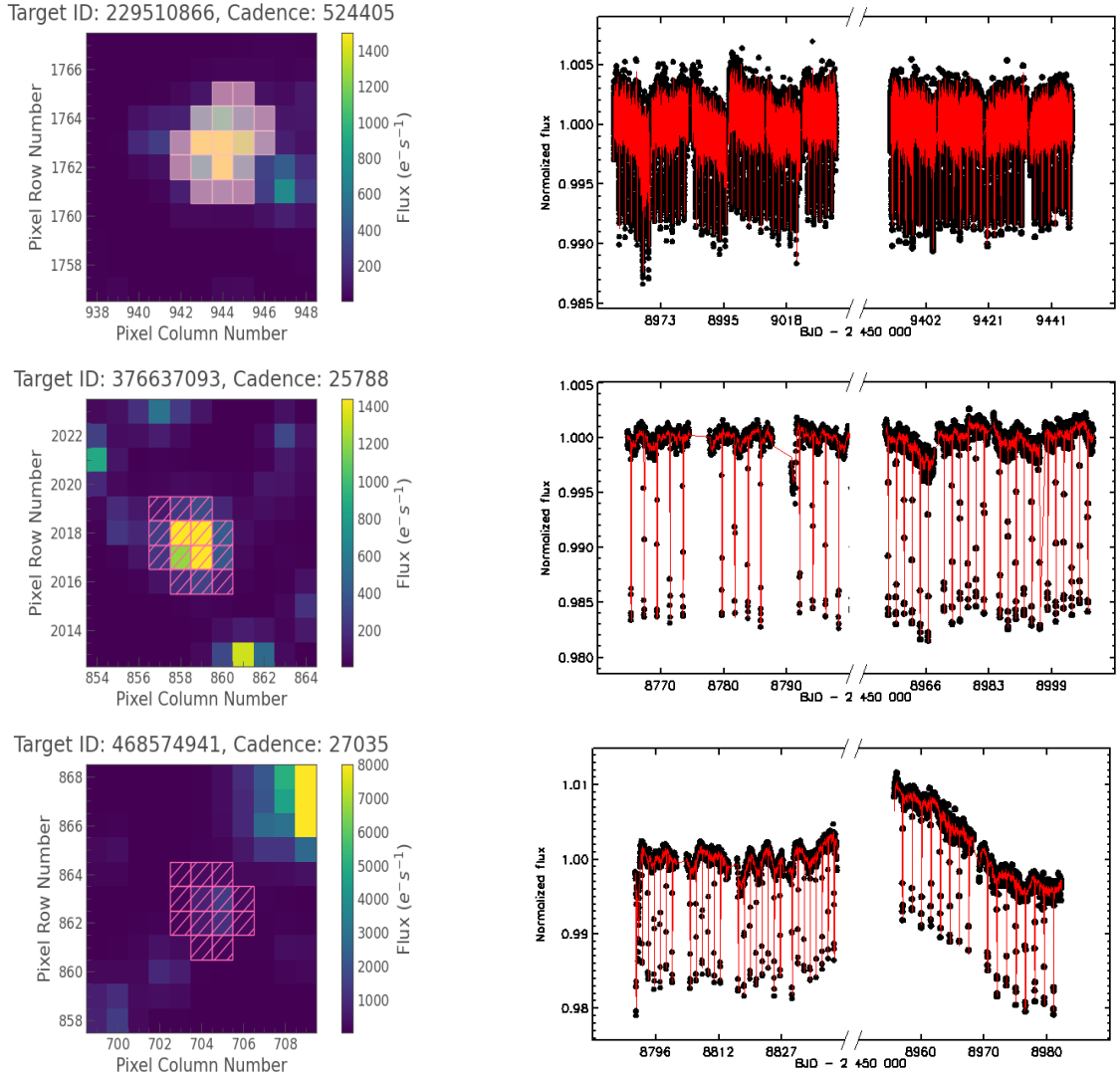
The *MUSCAT2* instrument is a four channel imager designed to observe simultaneously in the  $g$ ,  $r$ ,  $i$  and  $z_s$  photometric bands. It is installed on the 1.52 meter Carlos Sanchez Telescope (TCS) at the Teide Observatory in the Canary Islands, Spain. Each photometric channel is equipped with one  $1024 \times 1024$  CCD camera with a field of view of  $7.4 \times 7.4$  arcmin (Narita et al. 2019). One transit of TOI-1181b was observed with *MUSCAT2* on the night of 2019 November 9, using exposure times of 5, 7, 11 and 7 seconds for the  $g$ ,  $r$ ,  $i$  and  $k_s$  bands, simultaneously. The observations were taken slightly defocused and covered the full transit, with a average seeing trough the night of 1". The resulting light curve is plotted in Fig. A2. Table A1 presents the estimated posterior values of the parameters obtained from the full *MUSCAT2* light curve.

### 2.3 High-resolution imaging

Due to the large pixel scale of the *TESS* detectors, it is important to search for nearby contaminating sources that can dilute the transit depth or lead to false positives (e.g., Ciardi et al. 2015). In particular, those sources not detected in seeing-limited photometry or by Gaia require specialized observational techniques like high spatial resolution imaging to be detected.

On the nights of UT 2020 August 4 and 2021 June 29, we observed TOI-1181, TOI-1516, and TOI-2046 with the 'Alopeke speckle imager (Scott 2019), mounted on the 8.1 m Gemini North telescope at Mauna Kea. 'Alopeke has a field-of-view of 6.7" and it simultaneously acquires data in two bands centered at 562 nm and 832 nm using high-speed electron-multiplying CCDs (EMCCDs). We collected and reduced the data following the procedures described in Howell et al. (2011). The resulting reconstructed images achieved a contrast of  $\Delta mag \sim 4$  at a separation of  $0.2''$  in the 832 nm band (see Figure 2). No contaminants were found.

<sup>2</sup> <https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>



**Figure 1.** In the left hand panels, the cut-off images from the TPF files are presented with the photometric apertures in pink for stars TOI-1181 (upper panel), TOI-1516 (central panel) and TOI-2046 (bottom panel). The corresponding TESS-SPOC data pipeline processed light curves (SAP, black dots) for the three systems are shown in the right hand panels with the red fitted model obtained with the TLCM code described in Section 3.

**Table 1.** Observational characteristics of the host stars TOI-1181, TOI-1516 and TOI-2046.

| System                | TOI-1181   | TOI-1516   | TOI-2046   |
|-----------------------|--|--|--|
| TIC number            | TIC 229510866  | TIC 376637093  | TIC 468574941  |
| R.A.                  | 19 <sup>h</sup> 48 <sup>m</sup> 51 <sup>s</sup> .810 | 22 <sup>h</sup> 40 <sup>m</sup> 20 <sup>s</sup> .261 | 01 <sup>h</sup> 04 <sup>m</sup> 44 <sup>s</sup> .362 |
| Dec                   | +64° 21′ 15″.66                                      | +69° 30′ 13″.45                                      | +74° 19′ 52″.85                                      |
| Gaia parallax (mas)   | 3.22 ± 0.01  | 4.0540 ± 0.0098                                      | 3.47 ± 0.01  |
| TESS <sub>mag</sub>   | 10.079 ± 0.009                                       | 10.377 ± 0.006                                       | 10.996 ± 0.006                                       |
| V <sub>mag</sub>      | 10.582 ± 0.006                                       | 10.858 ± 0.008                                       | 11.552 ± 0.018                                       |
| Gaia <sub>mag</sub>   | 10.4776 ± 0.0003                                     | 10.7156 ± 0.0002                                     | 11.4128 ± 0.0005                                     |
| J <sub>mag</sub>      | 9.55 ± 0.02  | 9.92 ± 0.03  | 10.42 ± 0.02   |
| H <sub>mag</sub>      | 9.33 ± 0.02  | 9.70 ± 0.03  | 10.13 ± 0.03   |
| K <sub>mag</sub>      | 9.22 ± 0.02  | 9.67 ± 0.02  | 10.09 ± 0.02   |
| WISE <sub>3.4μm</sub> | 9.21 ± 0.02  | 9.60 ± 0.02  | 10.08 ± 0.02   |
| WISE <sub>4.6μm</sub> | 9.24 ± 0.02  | 9.63 ± 0.02  | 10.10 ± 0.02   |
| WISE <sub>12μm</sub>  | 9.24 ± 0.02  | 9.61 ± 0.03  | 10.00 ± 0.05   |
| WISE <sub>22μm</sub>  | 8.70 ± 0.19  | 9.41 ± 0.35  | 8.88 ± N/A   |



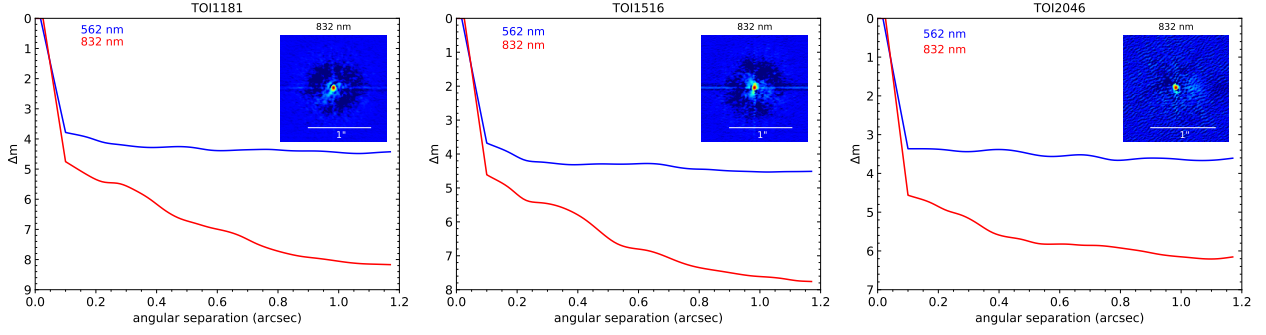


Figure 2. Speckle imaging results of TOI-1181, TOI-1516 and TOI-2046.

## 2.4 Spectroscopic follow-up

We performed spectroscopic follow-up using a network of mid-aperture sized telescopes in the northern hemisphere. These include the Ondřejov Echelle Spectrograph (OES) located in the Czech Republic, the Tautenburg echelle spectrograph (TCES) in Germany and the Tull Spectrograph at McDonald Observatory in the U.S.A. These provided the bulk of the data for the orbital solutions. All data sets were obtained between January 2020 and March 2021. The measured radial velocities are presented in Tabs. A2, A3 and A4.

### 2.4.1 The OES spectrograph

The Ondřejov Echelle Spectrograph (OES) is installed on the 2m telescope in Ondřejov, Czech Republic and is operated by the Astronomical Institute of the Czech Academy of Sciences. OES is a fiber-fed spectrograph with resolving power of  $R=50,000$  (at 500 nm) and wavelength range of 380–900 nm. An accuracy of 70 m/s in radial velocities is typically achieved for a  $V=6$  star. We use a hollow-cathode comparison frame for the wavelength calibration. A standard spectroscopic data reduction with IRAF scripts was performed on all data sets. The instrument related shifts are corrected by telluric lines using the method of Gray & Brown (2006) and radial velocities are obtained by the cross-correlation method using the `fxcor` task in IRAF. A more detailed description is provided in Kabáth et al. (2020). For the present targets and with an exposure time of 3600s, the typical Signal-to-Noise Ratio (SNR) of the OES spectra range between 20 and 40.

### 2.4.2 The TCES spectrograph

The Tautenburg Coudé Echelle spectrograph (TCES) is installed on the 2m Alfred Jensch telescope operated by the Thüringer Landessternwarte Tautenburg, Germany. The instrument achieves a resolving power of  $R=67,000$  over the wavelength range from 467 to 740 nm. The spectra can be calibrated with an iodine ( $I_2$ ) cell. The data reduction is performed with the Tautenburg Spectroscopy Pipeline –  $\tau$ -spline. The pipeline makes use of standard IRAF and PyRAF routines and the Cosmic Ray code by Malte Tewes based on the method by van Dokkum (2001). All steps are detailed in, e.g., Sabotta et al. (2019). The TCES can achieve an RV precision of 3–5 m/s on very bright stars with an iodine cell, but typical RV accuracy on fainter targets is about 70 m/s; for more details, see Guenther et al. (2009) and Döllinger et al. (2009). RVs were derived by a Python-

based software Velocity and Instrument Profile Estimator (VIPER)<sup>3</sup> (Zechmeister et al. 2021), based on the standard procedure described in Butler et al. (1996); Endl et al. (2000). Most of the spectra in Tautenburg were obtained with an iodine cell. Typical SNRs of the TCES spectra are in the range 10–20 with 1800 sec exposure time.

### 2.4.3 The Tull spectrograph

The Tull spectrograph is installed at the 2.7 m telescope of the McDonald Observatory operated by the University of Texas, USA. The instrument is a cross-dispersed white pupil echelle spectrograph. A  $2048 \times 2048$  pixel CCD at the “F3” focal position, combined with a 1.2 arcsec wide entrance slit gives a resolving power of about 60,000 over a wavelength range of 375 to 1020 nm. A temperature stabilized  $I_2$  vapor absorption cell placed in front of the slit provides the velocity metric. All data were reduced and extracted using an IRAF pipeline script. Precise radial velocities down to a few m/s were computed using the Austral pipeline (Endl et al. 2000).

### 2.4.4 The TRES spectrograph

We used the Tillinghast Reflector Echelle Spectrograph (TRES) on Mt. Hopkins, Arizona, to crosscheck and compare the stellar parameters with those derived from our data from the Tull, OES, and TCES spectrographs. During 2019, we obtained two spectra for each system of our targets. The spectrograph has a resolving power of  $R = 44000$  and covers wavelengths from 390nm to 910nm. The relative RVs that we derive from TRES spectra use multiple echelle orders from each spectrum that are cross-correlated with the highest S/N spectrum of the target star. We omit individual orders with poor S/N and manually remove obvious cosmic rays.

## 3 DATA ANALYSIS AND PARAMETERS DETERMINATION

In this section, we describe the methods used to analyse our data sets to determine the stellar parameters of the host stars such as radii, masses, effective temperatures, and metallicities, as well as their ages. The photometric light curves were also used to investigate stellar rotation.

<sup>3</sup> <https://github.com/mzechmeister/viper>

### 3.1 Fitting the light curves with TLCM

We used for our analysis the software package TRANSIT AND LIGHT CURVE MODELLER (TLCM, Csizmadia et al. 2021). This code is able to perform joint radial velocity and light curve fit, modelling the beaming, ellipsoidal and reflection effect (Faigler & Mazeh 2011; Shporer 2017; Wong et al. 2020). The noise model is based on the wavelet formulation of Carter & Winn (2009), with the regularization that the standard deviation of the residuals must converge to the average uncertainty of the input photometric data points, thereby avoiding overfitting. The approach was widely tested and the results have shown that, at the signal-to-noise ratio level of the present targets, the method is able to recover all the parameters with 1-2% accuracy (Csizmadia et al. 2021). We fit the transit parameters and the noise model simultaneously. Because of the noise-model applied here, we used the SAP-light curves for this kind of analysis and we kept only those data points with a quality flag of 0. The light curve was in the first step corrected for any potential contamination before modeling, using the CROWDSAP keyword of the TESS FITS-files.

The free parameters were: the scaled semi-major axis, the planet-to-star radius ratio, the impact parameter, and the limb darkening combinations of the quadratic limb darkening law as follows:

$$u_+ = u_a + u_b, u_- = u_a - u_b, \quad (1)$$

as well as the epoch, period, flux zero-level shift, wavelet-based noise model  $\sigma_w$ ,  $\sigma_r$ , the systematic velocity of the system ( $V_\gamma$ ), radial velocity amplitude ( $K$ ), and the radial velocity offsets between different spectrographs. Because only Full Frame Images (FFIs) with 30 minute integration time were available in the case of TOI-1516 and TOI-2046, we applied five subexposures and numerical integration to get more precise modelled flux values (cf. Section 2.11 of Csizmadia 2020). We have run a Genetic Algorithm/Harmony Search to optimize the joint light curve and radial velocity fit, with the results refined by three chains of Simulated Annealing. This yielded a starting point of the MCMC-analysis. We have run four chains for each system with a thinning factor of five. The chain lengths were at least 100,000 but they were automatically extended if they did not converge. The convergence was checked via the Gelman-Rubin statistic as well as via the estimated sample size. For details, see Csizmadia (2020) and references therein.

As a sanity check, we performed an independent joint analysis of the transit light curves and Doppler measurements of TOI-1181, TOI-1516, and TOI-2046 using the code `pyaneti` (Barragán et al. 2019), which infers the system parameters using a Bayesian approach coupled to Markov chain Monte Carlo simulations. We imposed uniform uninformative priors for all the model parameters and added photometric and RV jitter terms to account for noise not included in the nominal uncertainties. We initially fitted for the eccentricity and angle of periastron adopting the parametrization proposed by Anderson et al. (2011) and found that the eccentricities of the three planets are consistent with zero, with the Bayesian information criterion favouring circular models. We thus fixed the eccentricities to zero in our analysis. We found that the mean densities of the three stars – as derived from the modelling of the transit light curves using Kepler’s third law (Winn 2010) – are consistent with the spectroscopic densities. We also found that system parameters agree well within  $\sim 1\sigma$  with those derived with TLCM, corroborating our results.

### 3.2 TOI-1181 b: A hot Jupiter on a 2.1 day orbit around a subgiant star

We combine here *TESS* with the ground-based *CRCAO* and *MUSCAT2* photometric data and 57 spectra from OES, TCES and Tull spectrographs. The resulting RVs for all instruments used during the follow-up campaign are listed in Table A2. We also used the TRES spectra.

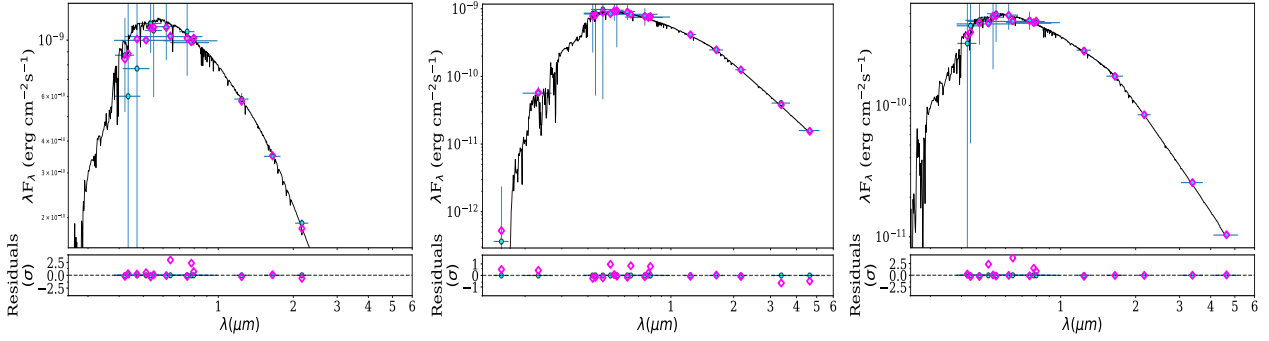
#### 3.2.1 The host star TOI-1181

First, we combined 13 best SNR spectra from Tautenburg’s TCES (i.e., only the spectra obtained without an Iodine cell and with a better SNR than the OES ones), in order to determine the stellar parameters of the host star. We used the *iSpec* software for the analysis (Blanco-Cuaresma et al. 2014; Blanco-Cuaresma 2019). Regions between 490 and 560 nm and between 605 and 627 nm were used to derive the effective temperature,  $T_{\text{eff}}$ , metallicity,  $[\text{Fe}/\text{H}]$ , surface gravity,  $\log g$  and rotational velocity of the star,  $v \sin i$ . We used the synthesis method from the code *SPECTRUM* and MARCS atmosphere models (Gustafsson et al. 2008). We also obtained parameters from the Tull spectra with the *KEA* pipeline (Endl & Cochran 2016), using synthetic spectra from the library compiled by Kurucz (1993). Another independent parameter set was derived from the analysis of the TRES spectra with *EXOFASTv2* (Eastman et al. 2019). The resulting values from these three independent analyses can be compared in Table 2. The same procedure applies for the other two systems discussed in this paper. It appears that the TRES and Tull values for  $[\text{Fe}/\text{H}]$  and  $\log(g)$  differ from the values derived with *iSpec*. The *iSpec* values were obtained manually by inspection of the spectra, while the TRES and Tull teams use automatized pipelines which might be biased towards main sequence stellar templates, but TOI-1181 is, as described in the following, an evolved star. Therefore, for further modelling, we use the *iSpec*-derived parameters for TOI-1181, that is, effective temperature  $T_{\text{eff}} = 5990 \pm 95$  K, gravity  $\log g = 3.9 \pm 0.15$  and  $v \sin i = 10.2 \pm 1.5$  km/s.

#### 3.2.2 Stellar parameters

We used the *ARIADNE*<sup>4</sup> code (Vines & Jenkins 2021) to determine the Spectral Energy Distribution function (SED) and the mass of the star by fitting the available measurements from various catalogues with various models, described below. The fitted SED of TOI-1181 is shown in the top panel of Figure 3. *ARIADNE* uses as input value the parallax from Gaia EDR3 (Gaia Collaboration et al. 2018, 2016) and models are obtained by convolution with Phoenix v2 (Husser et al. 2013), BT-Cond (Allard et al. 2012), BT-NextGen (Allard et al. 2012; Hauschildt et al. 1999), Castelli & Kurucz (Castelli & Kurucz 2006) and Kurucz (Kurucz 1993) models with the available photometric data in the following bandpasses: UBVRI; 2MASS JHKs; SDSS ugriz; ALL-WISE W1 and W2; Gaia G, RP, and BP; Pan-STARRS griwyz; Stromgren uvby; GALEX NUV and FUV; Spitzer/IRAC 3.6  $\mu\text{m}$  and 4.5  $\mu\text{m}$ ; TESS; Kepler; and NGTS. We also interpolated values for  $T_{\text{eff}}$ ,  $\log g$  and  $[\text{Fe}/\text{H}]$ . The stellar mass  $M_*$  was determined from MESA Isochrones and Stellar Tracks models (Dotter 2016). The corresponding derived parameters are reported in Table 2. We used

<sup>4</sup> <https://github.com/jvines/astroARIADNE>



**Figure 3.** The SED fitted by ARIADNE for TOI-1181 (top), TOI-1516 (center), TOI-2046 (bottom).

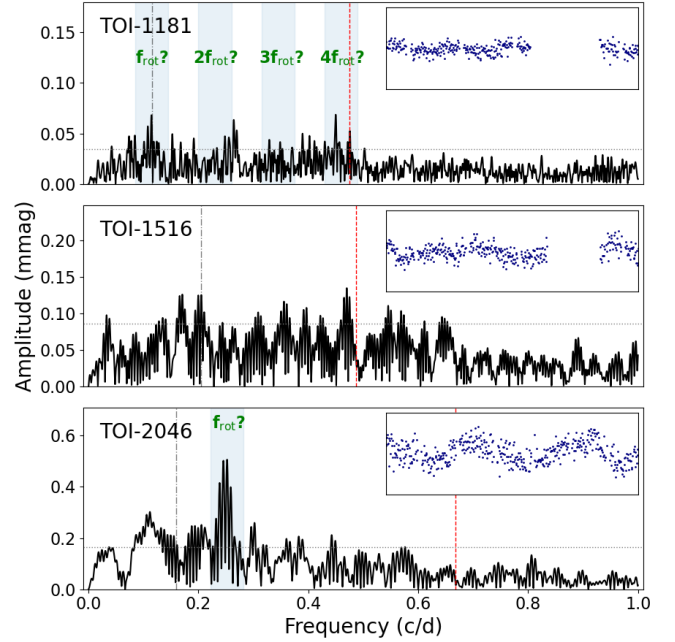
as priors the values of  $T_{\text{eff}}$ ,  $[\text{Fe}/\text{H}]$  and  $\log g$  determined from the spectra with *i*SPEC. ARIADNE derived for TOI-1181 a stellar mass of  $M_* = 1.38^{+0.086}_{-0.082} M_{\odot}$ , a radius of  $R_* = 1.9^{+0.06}_{-0.10} R_{\odot}$  and an age of  $2.59^{+0.43}_{-0.51}$  Gyr.

We further derived the spectral type and luminosity class of TOI-1181 following the method outlined in Frasca et al. (2003) and Gandolfi et al. (2008). Briefly, we fitted the iodine-free Tull spectra of the three stars using the Indo-US grid of stellar templates from Valdes et al. (2004). Prior to the fitting procedure, the resolution of the Tull spectra was degraded to match that of the templates ( $R=5,500$ ) by convolving the Tull spectra with a Gaussian function mimicking the difference between the two instrument profiles. The radial velocity shift between the Tull spectra and Indo-US templates was measured using the cross-correlation technique. We fitted the 4500–6800 Å spectral range, masking out the regions containing telluric lines. We found that TOI-1181 is a somewhat evolved F9 IV star. Further discussion on TOI-1181 is provided in Sec 4.

### 3.2.3 Stellar rotation

To investigate the light variations out of eclipse and their possible connection with stellar variability, we used the PDCSAP data with 1800s cadence<sup>5</sup>. After we removed the transits from the light curves, we performed a discrete Fourier transform on the full data sets by using the PERIOD04 software (Lenz & Breger 2005) to get the periodograms (Fig. 4). The frequency spectra of all the three studied stars show peaks above the significance limit defined by  $\text{SNR} > 4$  (Breger et al. 1993). To test the nature and stability of the identified peaks, we divided the data sets into segments spanning 20–30 days and performed the frequency analysis on these shorter data sets.

In TOI-1181, we identified three significant peaks at 0.449, 0.264 and 0.114 c/d (periods of 2.22, 3.78 and 8.74 days – top panel of Figure 4). The peak corresponding to the period of 8.74 days perfectly matches the rotational period calculated from  $v \sin i$  (assuming  $i = 87^\circ$ ) and stellar radius ( $R_* = 1.75 R_{\odot}$ ),  $P_{\text{rot}} = 8.7 \pm 1.4$  days (the dash-dotted line in the top panel of Fig. 4). We detected this frequency and its harmonics also in all the subsets, therefore making unlikely the instrumental origin of this frequency peak. It is highly likely that these peaks are real and attributed to the rotational period of the



**Figure 4.** The frequency spectra of the residual light curves (without transits) for the investigated stars. The red dashed vertical line shows the position of the orbital frequency, the grey dash-dotted line shows the position of the expected rotational period calculated from  $v \sin i$  and the stellar radius, while the grey dotted lines show the reliability  $\text{SNR} = 4$  level for the highest peak. The insets show the 10-days segments of the light curves. The vertical range of the insets is 6 mmag.

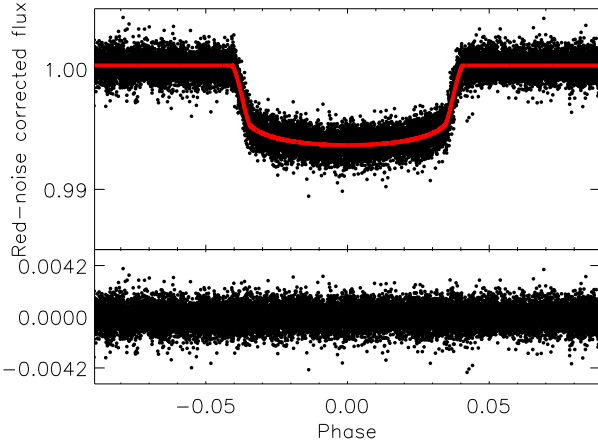
star. The differential rotation and spots at different latitudes are most likely responsible for the slight difference of the frequency peaks of the harmonics.

### 3.2.4 Stellar pulsations

We also performed a seismic analysis to look for solar-like oscillations using the TESS lightcurves. To do so we used two types of lightcurves: the PDCSAP lightcurves and lightcurves obtained with a customized aperture larger than the previous one and that is optimized for asteroseismology. For that second dataset, we selected pixels in the target pixel files where the average flux is above 100  $e^-/s$  and making sure that we do not pick pixels contaminated by a nearby star. For both lightcurves we removed the planetary transits,

<sup>5</sup> Downloaded using LIGHTKURVE v 2.0 package (Lightcurve Collaboration et al. 2018) because the SAP data suffer from strong instrumental effects (see the right-hand panels of Fig. 1).





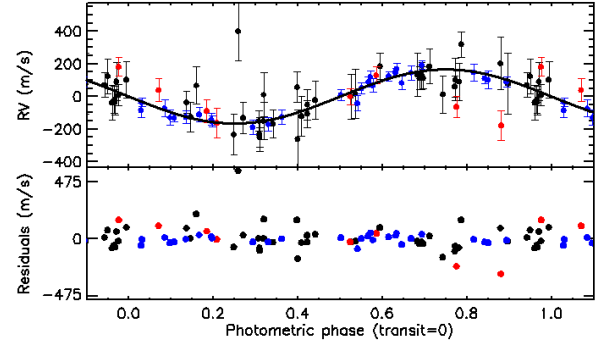
**Figure 5.** Upper panel: the red-noise corrected *TESS* SAP-fluxes (black dots = observations - red noise component) of TOI-1181 as a function of phase. The model fit is shown with red solid lines. Results obtained by TLMC (see Section 3.1). Lower panel: the residuals of the model fit after subtracting the red noise component from the observations.

outliers, and filled the gaps following [García et al. \(2011, 2014\)](#). Using global seismic scaling relations ([Brown 1991](#); [Kjeldsen & Bedding 1995](#)) where we combined the effective temperature and the surface gravity, we estimated the predicted frequency of maximum power,  $\nu_{\max}$ , to be around  $1000 \mu\text{Hz}$ . From the visual inspection of the power spectrum density (PSD) computed for both lightcurves, no obvious acoustic-mode bump is visible around that value. We ran the A2Z pipeline ([Mathur et al. 2010](#)) to look for the signature of the modes, without success.

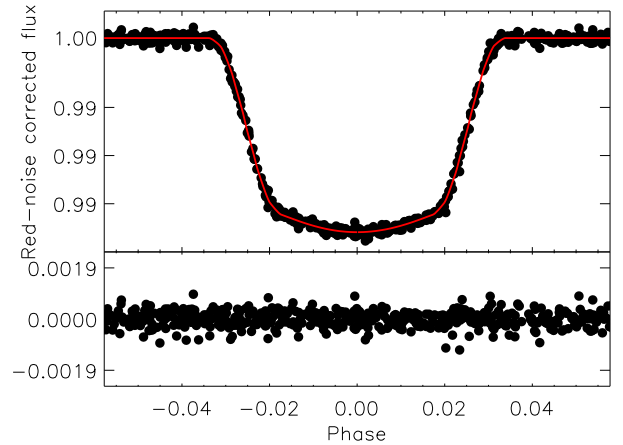
We also computed the predicted amplitude of the modes according to the seismic scaling relations taking  $T_{\text{eff}}=6000\text{K}$  and the Gaia luminosity of the star. We found a predicted amplitude of 5-6 ppm. In Fig. A3, we show that the amplitude spectrum between 500 and  $200 \mu\text{Hz}$  is completely flat, dominated by the noise with a mean value of 6.6 ppm which is higher than the expected amplitude of the modes. If the star was more evolved (late subgiant or early red giant), the modes would have been at lower frequency with higher amplitudes and we would have detected them. Thus we can only conclude that the star could either be on the main sequence or an early subgiant, which is consistent with our age determination. The graphs for our analysis are presented in Appendix A3.

### 3.2.5 TOI-1181b is a hot Jupiter around a subgiant

As explained above, in order to derive the planetary parameters and the orbital solution, we performed a joint fit with the TLMC package that combined all data sets from the spectroscopic instruments and from *TESS*. The fitted ratio of  $R_{\text{planet}}/R_*$  and inclination  $i = 87.0^\circ \pm 1.3^\circ$  combined with the stellar radius  $R_*$  provides a planetary radius  $R_{\text{planet}} = 1.30 \pm 0.08 R_J$ . The planetary mass from the spectroscopic data and inclination  $i$  results in  $M_{\text{planet}} = 1.18 \pm 0.14 M_J$ . An orbital period  $P = 2.103195^{+0.000012}_{-0.000011}$  was derived from the fit. All fitted parameters, for each instrument, are presented in Table 2. The folded *TESS* light curve is presented in Fig. 5 and RVs are presented in Fig. 6. Based on all our solutions, we are thus seeing a star which left the main sequence just recently and which is orbited by a hot Jupiter.



**Figure 6.** Upper panel: phase-folded radial velocity measurements of TOI-1181. The black dots are the TCES measurements, the red dots the OES measurements, while the blue ones represent RVs obtained by the Tull spectrograph. The black solid line shows the circular orbit fit. Lower panel: residuals of the radial velocity fit (in m/s).



**Figure 7.** Same as Fig. 5 for TOI-1516.

## 3.3 TOI-1516b: A hot Jupiter with a 2.05 day period

We used the *TESS* light curve and spectroscopic data from Tautenburg, Ondřejov and McDonald observatories for a joint fit. In total we used 81 spectra from all three observatories.

### 3.3.1 The host Star TOI-1516

We stacked 9 spectra from Ondřejov in order to determine the stellar parameters of the host star. The derivation of stellar parameters with iSpec revealed that the host star has an effective temperature  $T_{\text{eff}} = 6520 \pm 90 \text{ K}$ , a metallicity  $[\text{Fe}/\text{H}] = -0.05 \pm 0.1$ , surface gravity,  $\log g = 4.25 \pm 0.15 \text{ cm s}^{-2}$  and  $v \sin i = 11.8 \pm 1.5 \text{ km/s}$ . All parameters are presented in the corresponding central column of Table 2. The spectral type and luminosity class found from our spectra as described in 3.2.1 is F8V.

A periodogram analysis was performed on the *TESS* data for TOI-1516. The dominant peak was found to be at  $0.470 \text{ c/d}$  (2.13 days), complemented with a group of other peaks in the low-frequency regime (the middle panel of Figure 4). We detected a peak at the

**Table 2.** System parameters for host stars of hot Jupiters TOI-1181, TOI-1516 and TOI-2046 obtained by TLMC. Stellar mass and radius are derived from isochrone-fitting as described in Csizmadia (2020).

| Parameter                            | Instrument     | TOI-1181b                          | TOI-1516b                          | TOI-2046b                             |
|--------------------------------------|----------------|------------------------------------|------------------------------------|---------------------------------------|
| $a/R_*$                              |                | $4.19^{+0.06}_{-0.08}$             | $6.22^{+0.041}_{-0.077}$           | $4.75^{+0.18}_{-0.17}$                |
| $R_{\text{planet}}/R_*$              |                | $0.0764^{+0.0004}_{-0.0004}$       | $0.1224^{+0.0005}_{-0.0005}$       | $0.1213^{+0.0017}_{-0.0021}$          |
| $b$                                  |                | $0.19^{+0.08}_{-0.11}$             | $0.09^{+0.10}_{-0.07}$             | $0.51^{+0.06}_{-0.07}$                |
| $u_+$                                |                | $0.46^{+0.06}_{-0.06}$             | $0.10^{+0.08}_{-0.08}$             | $0.39^{+0.24}_{-0.16}$                |
| $u_-$                                |                | $0.16^{+0.19}_{-0.19}$             | $0.81^{+0.19}_{-0.19}$             | $0.30^{+0.59}_{-0.74}$                |
| Epoch (BJD)–2 450 000                |                | $8684.4058^{+0.0017}_{-0.0017}$    | $8765.3250^{+0.0001}_{-0.0001}$    | $7792.2767^{+0.0024}_{-0.0022}$       |
| Period (days)                        |                | $2.103195^{+0.000012}_{-0.000011}$ | $2.056014^{+0.000002}_{-0.000002}$ | $1.4971842^{+0.0000031}_{-0.0000033}$ |
| $\sigma_r$ (ppm)                     |                | $34469^{+589}_{-584}$              | $14950^{+252}_{-252}$              | $24024^{+471}_{-469}$                 |
| $\sigma_w$ (ppm)                     |                | $1046^{+3}_{-3}$                   | $299^{+4}_{-4}$                    | $576^{+14}_{-14}$                     |
| $V_\gamma$ (m/s)                     |                | $119.1^{+15.7}_{-15.8}$            | $-397.6^{+39.5}_{-40.7}$           | $-12.6^{+5.5}_{-5.5}$                 |
| $K$ (m/s)                            |                | $165.6^{+11.4}_{-11.4}$            | $460.7^{+9.0}_{-9.0}$              | $374.7^{+7.8}_{-7.8}$                 |
| RV-offsets (m/s)                     |                |                                    |                                    |                                       |
| Ondrejov - TCES                      |                | $-118.5^{+34.6}_{-34.5}$           | $-116.0.2^{+44.9}_{-43.1}$         |                                       |
| Tull-TCES                            |                | $-50477.5^{+17.1}_{-17.2}$         | $-48189.7^{+41.3}_{-40.0}$         |                                       |
| TCES - Tull                          |                |                                    |                                    | $537.7^{+49.4}_{-49.4}$               |
| Ondrejov - Tull                      |                |                                    |                                    | $-9479.6^{+43.3}_{-43.2}$             |
| Derived parameters                   |                |                                    |                                    |                                       |
| Inclination ( $^\circ$ )             |                | $87.0^\circ \pm 1.3^\circ$         | $90.0^\circ \pm 0.4^\circ$         | $83.6^\circ \pm 0.9^\circ$            |
| Transit duration (hrs)               |                | $4.057^{+0.014}_{-0.013}$          | $2.826^{+0.015}_{-0.014}$          | $2.410^{+0.032}_{-0.030}$             |
| $\rho_*$ ( $kg/m^3$ )                |                | $312 \pm 16$                       | $1090 \pm 31$                      | $890 \pm 98$                          |
| $M_*/M_\odot$                        |                | $1.19 \pm 0.18$                    | $1.14 \pm 0.06$                    | $1.13 \pm 0.19$                       |
| $R_*/R_\odot$                        |                | $1.75 \pm 0.09$                    | $1.14 \pm 0.02$                    | $1.21 \pm 0.07$                       |
| $M_{\text{planet}}/M_J$              |                | $1.18 \pm 0.14$                    | $3.16 \pm 0.12$                    | $2.30 \pm 0.28$                       |
| $R_{\text{planet}}/R_J$              |                | $1.30 \pm 0.08$                    | $1.36 \pm 0.03$                    | $1.44 \pm 0.11$                       |
| Stellar parameters                   |                |                                    |                                    |                                       |
| $T_{\text{eff}}$ [K]                 | Tull           | $6260 \pm 100$                     | $6420 \pm 100$                     | $6160 \pm 100$                        |
| $T_{\text{eff}}$ [K]                 | iSPEC OES/TCES | $5990 \pm 95$                      | $6520 \pm 90$                      | $6250 \pm 140$                        |
| $T_{\text{eff}}$ [K]                 | TRES           | $6177 \pm 50$                      | $6170 \pm 52$                      | $6143 \pm 97$                         |
| $\log g$ [cgs]                       | Tull           | $4.31 \pm 0.18$                    | $4.25 \pm 0.18$                    | $4.38 \pm 0.18$                       |
| $\log g$ [cgs]                       | iSPEC OES/TCES | $3.9 \pm 0.15$                     | $4.25 \pm 0.15$                    | $4.3 \pm 0.15$                        |
| $\log g$ [cgs]                       | TRES           | $4.27 \pm 0.08$                    | $4.18 \pm 0.22$                    | $4.35 \pm 0.08$                       |
| Fe/H [dex]                           | Tull           | $0.30 \pm 0.12$                    | $-0.14 \pm 0.12$                   | $0.04 \pm 0.12$                       |
| Fe/H [dex]                           | iSPEC OES/TCES | $0.05 \pm 0.1$                     | $-0.05 \pm 0.1$                    | $-0.06 \pm 0.15$                      |
| Fe/H [dex]                           | TRES           | $0.44 \pm 0.08$                    | $-0.05 \pm 0.1$                    | $0.29 \pm 0.08$                       |
| $v_{\text{sini}}$ [km/s]             | Tull           | $10.77 \pm 0.30$                   | $11 \pm 0.4$                       | $8.15 \pm 0.15$                       |
| $v_{\text{sini}}$ [km/s]             | iSPEC OES/TCES | $10.2 \pm 1.5$                     | $11.8 \pm 1.5$                     | $9.8 \pm 1.6$                         |
| $v_{\text{sini}}$ [km/s]             | TRES           | $11.8 \pm 2.0$                     | $13.8 \pm 2.0$                     | $8.8 \pm 2.0$                         |
| Derived stellar parameters (ARIADNE) |                |                                    |                                    |                                       |
| Stellar radius - $R_*$ ( $R_\odot$ ) |                | $1.90^{+0.06}_{-0.10}$             | $1.245^{+0.031}_{-0.032}$          | $1.237^{+0.036}_{-0.032}$             |
| Stellar mass - $M_*$ ( $M_\odot$ )   |                | $1.380^{+0.086}_{-0.082}$          | $1.085^{+0.061}_{-0.066}$          | $1.153^{+0.10}_{-0.093}$              |
| Age of the host star (Gyr)           |                | $2.59^{+0.43}_{-0.51}$             | $4.82^{+2.44}_{-1.29}$             | $0.45^{+0.43}_{-0.021}$               |
| Spectral type                        |                | F9IV                               | F8V                                | F8V                                   |

expected rotational frequency calculated from  $v \sin i$  and stellar radius (the grey dash-dotted line in Fig. 4) also in one of the subsets. However, the detection is inconclusive.

We used ARIADNE to fit the SED and to determine the stellar pa-

rameters and age of the system. We used the derived stellar values from Table 2 as priors for ARIADNE. The SED obtained from the available photometric data as described in the Section 3.2.1 is depicted in the central panel of Figure 3. The stellar mass from the isochrones was determined as  $M_* = 1.085^{+0.061}_{-0.066} M_\odot$  and the stellar

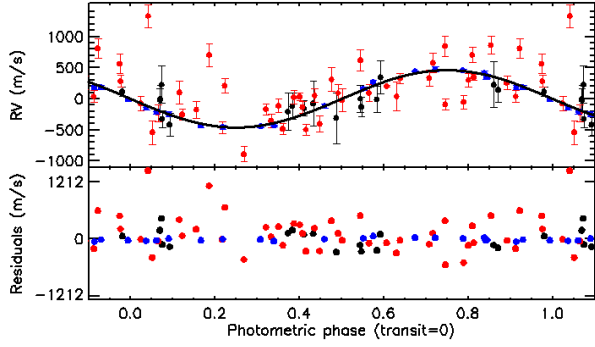


Figure 8. Same as Fig. 6 for TOI-1516.

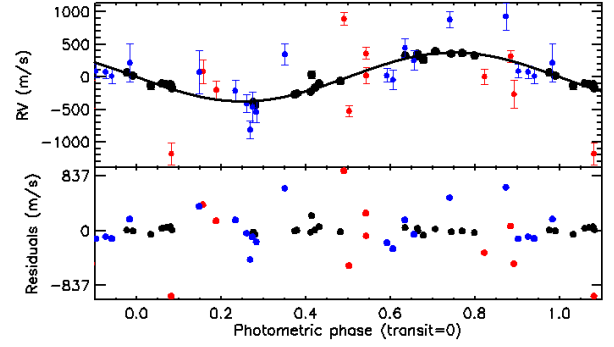


Figure 10. Same as Fig. 6 for TOI-2046.

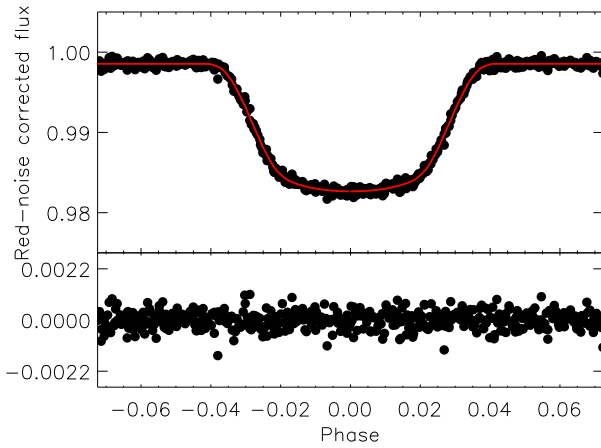


Figure 9. Same as Fig. 5 for TOI-2046.

radius  $R_* = 1.245^{+0.031}_{-0.032} R_\odot$ . The age of the host star was determined as  $4.82^{+2.44}_{-1.29}$  Gyr. For the derivation of the above parameters, the Gaia EDR3 parallax  $\varpi = 4.0540 \pm 0.0098$  mas was used.

### 3.3.2 Planet TOI-1516b is another ordinary hot Jupiter

We performed a joint fit with TLMCM. We performed the first fit with eccentricity as a free parameter and based on the result being consistent with a circular orbit, we fixed the eccentricity  $e$  at 0. Other parameters were left free. The resulting folded light curve from *TESS* is presented in Figure 7 and the RVs are shown in Fig 8. The values of the fit confirm that TOI-1516 b is a hot Jupiter with a 2.06 day orbital period. The values for the mass and the radius are  $M = 3.16 \pm 0.12 M_J$  and  $R = 1.36 \pm 0.03 R_J$ , respectively. The derived parameters for the system imply an ordinary hot Jupiter around an F-type main sequence star.

## 3.4 The young system TOI-2046

We used data from *TESS* and from the Tautenburg, Ondřejov and McDonald observatories. In total, we used 51 spectra from all three observatories. The corresponding RVs are listed in Table A3.

### 3.4.1 The host star TOI-2046

We stacked 7 spectra from Ondřejov in order to determine the stellar parameters of the host star. Our analysis with *iSpec* resulted in the following parameters for the host star:  $T_{\text{eff}} = 6250 \pm 0.140$  K, metallicity  $[\text{Fe}/\text{H}] = -0.06 \pm 0.15$ , surface gravity,  $\log g = 4.3 \pm 0.15$   $\text{cm s}^{-2}$ , and  $v \sin i = 9.8 \pm 1.6$  km/s. All relevant physical parameters are presented in the right column of Table 2. The spectral type and luminosity class determined as described in Sec 3.2.1 is F8V.

### 3.4.2 Stellar activity

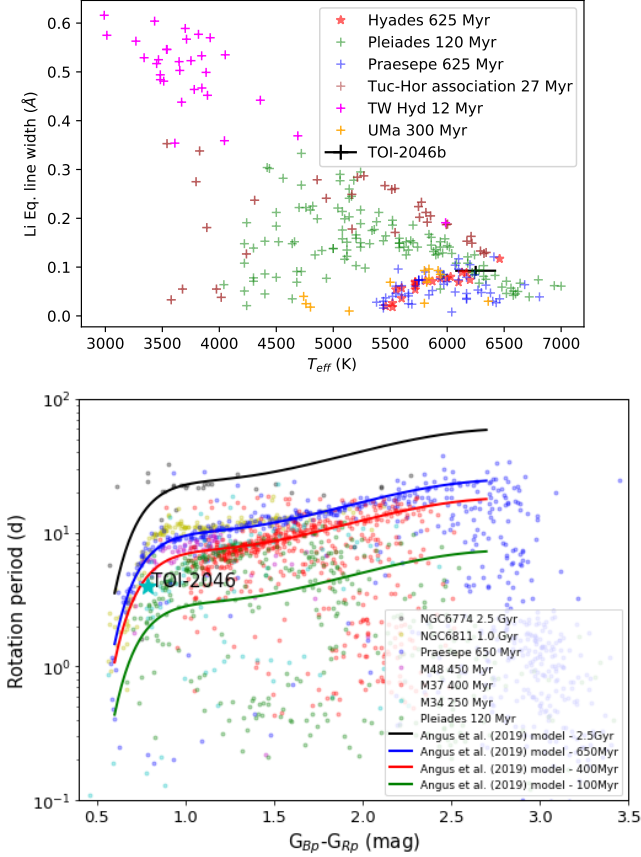
The dominant peak in the frequency spectrum of the full data set of TOI-2046 with the transit signature removed is at 0.252 c/d (period of 3.97 days) with a  $\text{SNR} > 12$ . To test the stability and reliability of the detected peak, we split the full data set into two subsets divided by the large gap between observations in sectors 18+19 (subset 1) and sectors 24 (subset 2) – see the bottom right-hand panel of Fig 1. The peak is present in both subsets and has similar amplitude (blue and red lines in the bottom right-hand panel of Fig. 4).

The flux variations with the 4-days period are clearly apparent from the inset of the bottom panel of Fig. 4. The detection of the peak in the two subsets separated by more than 100 days shows that the frequency is stable over time. Thus, we assume that the variations are real (i.e., not instrumentals) and can be attributed to the stellar rotation with a period of 3.97(2) days.

The value of the detected rotational period significantly differs from the period calculated from  $v \sin i$  and stellar radius ( $P_{\text{rot}} \approx 6.2$  days). This may indicate that the rotational axis of the star and the orbital-plane axis of the planet are not aligned. The inclination of the rotational axis would be approximately 39 degrees which is significantly different from the orbital inclination of the planet (83.6 deg).

### 3.4.3 Stellar age

ARIADNE yields an age of  $0.45^{+0.43}_{-0.02}$  Gyr for TOI-2046, indicating that this is one of the few very young known planetary systems. We tried to confirm the young age of the star using the Li line, which can be used as an indication of stellar youth. We measured the equivalent widths (EW) of a Gaussian fit to the Li line at 6707 Å:  $\text{EW} = 0.083 \pm 0.01$  Å. The EW and the derived stellar temperature from Table 2 were compared with available data from open clusters



**Figure 11.** The top panel shows the equivalent widths of the 6708 Å Li I line versus the effective temperatures for stars in selected young clusters and associations of different ages. The bottom panel presents the stellar rotational period versus their Gaia color index for stars in several clusters, together with some models of cluster evolution represented with solid lines (Angus et al. 2019). In both panels, the data are from Soderblom et al. (1993b, 1990); Mentuch et al. (2008); Soderblom et al. (1993a) and the position of TOI-2046b is indicated.

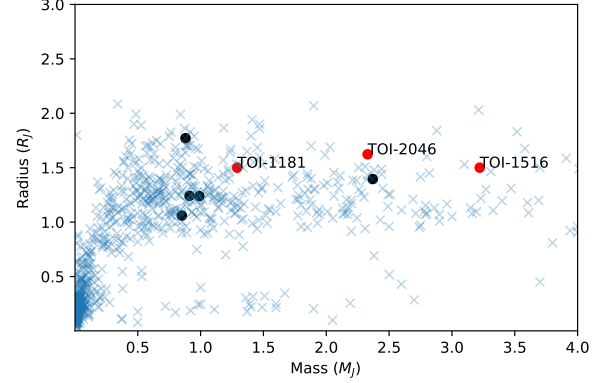
of various ages, shown in Figure 11. A further discussion of the age of this particular system is provided in Sec. 4

#### 3.4.4 A young hot Jupiter TOI-2046b

The folded *TESS* light curve is presented in Figure 9 and the RVs in Figure 10. The parameters of the planet from the joint fit with the TLCDM package confirm that TOI-2046b is a hot Jupiter on an orbit with a 1.49 day period and a combination with stellar parameters allows for the determination of mass  $M = 2.30 \pm 0.28 M_J$  and radius  $R = 1.44 \pm 0.11 R_J$ .

## 4 NEW GAS PLANETS IN CONTEXT WITH OTHER GIANT PLANETS

In this section we will discuss the parameters of the newly discovered hot Jupiters in the context of similar systems.



**Figure 12.** Mass-radius diagram of all known exoplanets with our three new systems represented by red dots. The black dots are some other recently discovered *TESS* gas giants (Rodríguez et al. 2021), shown for comparison.

### 4.1 Mass-Radius diagram

The natural metrics for comparison of planets is the mass-radius diagram. We present the mass-radius diagram with the new *TESS* giant planets from this paper and plot them with all known planets which have parameters available in THE EXTRASOLAR PLANETS ENCYCLOPEDIA<sup>6</sup>. The three hot Jupiters described in this paper exhibit rather larger radii, as can be seen in Figure 12. We also show in the figure a set of recently discovered *TESS* hot Jupiters (Rodríguez et al. 2021) as a comparison with similar planets.

### 4.2 Incident flux from the host star and exo-atmospheres

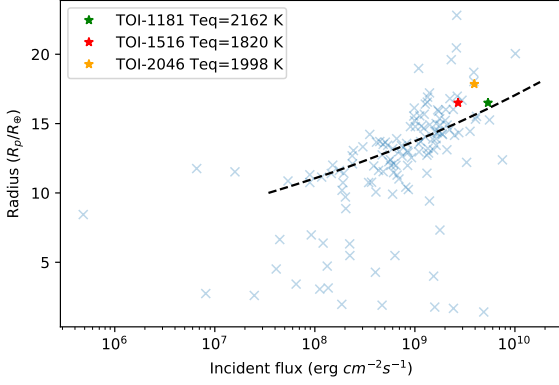
We further investigated the incident flux from the host star at the planetary surface. For our three targets, we used Gaia DR2 and the luminosities determined with the *FLAMES* pipeline (Bailer-Jones et al. 2013). The resulting insulations are presented in Fig. 13, where the planetary equilibrium temperatures are also indicated. In the same Figure, as a dashed line, we plot the empirical relationship for one Jupiter-mass gas planets derived by Weiss et al. (2013, their Eq. 9):

$$\frac{R_p}{R_\oplus} = 2.45 \left( \frac{M_p}{M_\oplus} \right)^{-0.039} \left( \frac{F}{\text{erg.s}^{-1}.\text{cm}^{-2}} \right)^{0.094}, \quad (2)$$

where  $F$  is the incident flux and  $R_p$  and  $M_p$  are the planet's radius and mass.

The three hot Jupiters reported in this paper receive higher incident flux from their host star compared to the majority of known planets. The highest insolation is consistent with the subgiant status of TOI-1181b, but TOI-2046b also undergoes high insolation and is most likely inflated. Therefore, these systems might in principle be reasonable candidates for further follow-up observations to detect their atmospheric signatures. For this reason, we calculated the expected atmospheric signal for performing transmission spectroscopy. We followed the approach from Kabáth et al. (2019) and we first determined the expected signature of exoatmosphere  $\Delta\delta$  roughly given by:

<sup>6</sup> <http://exoplanet.eu/catalog>



**Figure 13.** Radius versus incident flux for the three hot Jupiters from this paper including their equilibrium temperatures. Other known planets are represented by blue crosses. The dashed line represents the empirical relation from Weiss et al. (2013) for Jupiter-mass planets (Eq. 2).

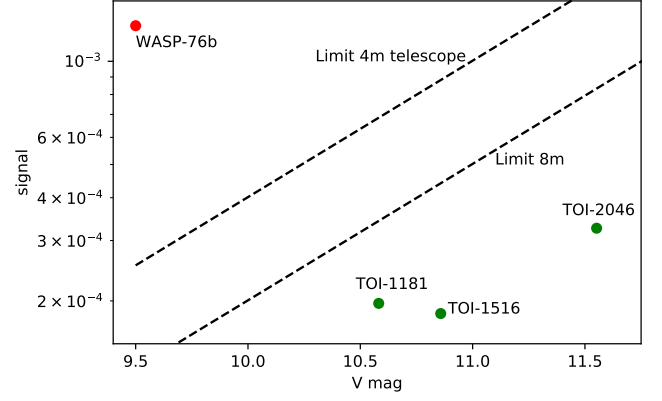
$$\Delta\delta \approx \frac{2nHR_P}{R_S^2}, \quad (3)$$

where  $n$  is the number of atmospheric scale heights  $H$ . Here we assume  $n = 6$  which is valid for high altitudes and typical for Na species abundant in gas giants. The expected signal for the three new hot Jupiters is presented in Figure 14. We used as a reference a successful detection of the NaD features in the exoatmosphere of Wasp-76b and scaled down the detection limit at  $3\sigma$  represented with a dashed line for a 4 m telescope and for an 8 m telescope. The three new planets have clearly an expected atmospheric signature too faint to be detected from the ground. However, the transmission signal  $\Delta\delta = 326$  ppm from TOI-2046b should be clearly detectable by *JWST*, assuming the detection floor of 20 ppm for GJ1214b (Kreidberg et al. 2014; Greene et al. 2016) and taking into account the fact that our star is about 1.5 mag fainter in the K-band. Planets TOI-1181b and TOI-1516b would be definitively more challenging targets.

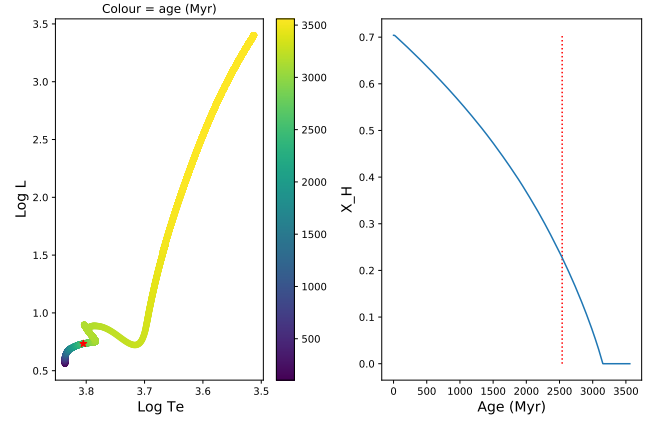
The high incident flux and relatively high atmospheric equilibrium temperatures make these targets interesting for detection of occultation of the planet by the star. Our team therefore analysed in detail the phased *TESS* light curves of these candidates with respect to the reflected light from the planet and new results will be presented in a separate paper (Csizmadia 2021) for TOI-1181b. However, it would be interesting to search for an occultation of TOI-2046b due to its rather high insolation and inflated atmosphere. The limiting factor for *TESS* is that TOI-2046 is one magnitude fainter than TOI-1181, leading to a much worse precision, and the analysis of the TOI-2046 *TESS* light curve is inconclusive.

#### 4.3 A giant planet around a subgiant star

We know much less planets orbiting evolved stars than planets around main sequence stars. New planetary systems around evolved stars hosting a hot Jupiter were reported, e.g., with *Kepler* and *K2*, but also with *TES* (Van Eylen et al. 2016; Grunblatt et al. 2017; Döllinger et al. 2007). Planets around evolved stars usually show slightly larger eccentricities compared to planets around main sequence stars – the



**Figure 14.** Expected signal of a planetary atmosphere, representative of the possible detection of the planet’s NaD lines by transmission spectroscopy. We also show the position of Wasp-76b, a reference system with a clear detection of Na, while the dashed lines show the detection limit for two classes of telescopes.

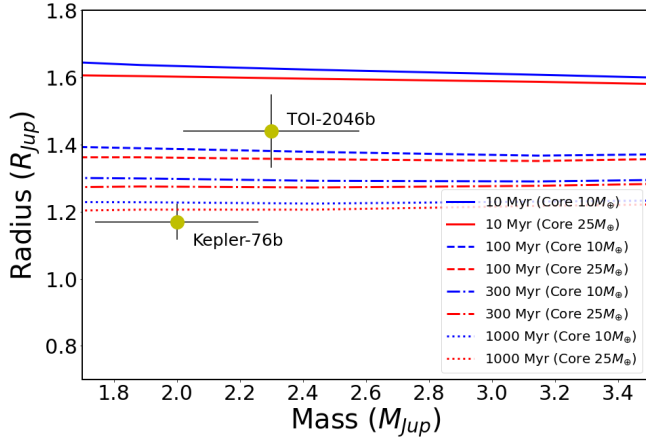


**Figure 15.** Left panel: PARSEC evolutionary track in the Hertzsprung-Russell diagram of a  $1.38 M_{\odot}$  star, corresponding to TOI-1181. The colours correspond to the age of the star (in Gyr), and the current position of TOI-1181 is indicated with the red dot. Right panel: Fraction of remaining hydrogen in the core of the star, based on the PARSEC track, as a function of age, with the estimated age of TOI-1181 indicated with the vertical line.

median for hot Jupiters main sequence stars is  $0.056^{+0.022}_{-0.006}$ , while for hot Jupiters around evolved stars it is  $0.152^{+0.077}_{-0.042}$  (Grunblatt et al. 2018). However, in our case, we found the eccentricity of TOI-1181b to be consistent with zero. This system is also interesting due to its age of  $2.59^{+0.43}_{-0.51}$  Gyr which is around the tipping point where the star leaves the main sequence and evolves towards the red giant branch, as can be seen in Fig. 15 which shows a PARSEC evolutionary track (Bressan et al. 2012). A star with a mass of  $1.38 M_{\odot}$  has left the main sequence at the age of TOI-1181, even if its core still contains about 20% of hydrogen.

The Gaia luminosity from DR2 data corresponds to  $L = 4.45 \pm 0.08 L_{\odot}$ . The derived  $T_{\text{eff}} = 5990 \pm 95$  K corresponds to a F9 type star, but the radius  $R = 1.9 R_{\odot}$  is too large for a main sequence star. The Gaia radius for the star TOI-1181  $R_{*} = 2.03 \pm 0.07 R_{\odot}$  is even larger than our values and it is also indicating an evolved star. The very early stage of the subgiant branch for this star is suggested also





**Figure 16.** Mass-radius diagram with isochrones, according to thermal model by Fortney et al. (2007).

by our asteroseismologic analysis presented in Sec. 3.2.4 as we did not detect any pulsations typical for later stages of giant stars. The star rotates still relatively fast but when compared with the sample in, e.g., do Nascimento et al. (2003), its rotation is consistent with a subgiant branch stars as can be seen in their Fig. 1. Therefore, tidal locking might play a role in a slower braking of the stellar rotation. From the presented analysis and from our spectral analysis described earlier, it can be concluded that we are seeing here an early subgiant star which entered its inflationary phase.

#### 4.4 A very young hot-Jupiter system around TOI-2046

We now turn to the age of the TOI-2046 system and put it in context of other similar systems. Figure 11 implies that the system TOI-2046 is a relatively young system, with an age between 27 Myr (Tucanae-Horologium association, Mentuch et al. 2008) and 625 Myr as a very conservative estimate (Praesepe or Hyades, Soderblom et al. 1993b, 1990). We also investigated the Gaia color indices and rotational periods of selected young clusters and compared them to the TOI-2046 system’s parameters (see bottom of Figure 11) as well as to evolutionary models of young clusters from Angus et al. (2019). The comparison of stellar rotational period constrains the age between 120–400 Myr. However, we remark that tidal spin-up would need to be taken into account if present (Tejada Arevalo et al. 2021).

We used the thermal evolution model (Fortney et al. 2007) to determine the core mass of this young system. As input parameters for the isochrones in the mass-radius graph, we use the systems parameters, the luminosity and a distance from Gaia DR2 and EDR3 release, respectively. In Fig. 16, we show the isochrones in the mass radius diagram for different core sizes and we compare the planet TOI-2046b with Kepler-76b (Faigler et al. 2013), which has similar parameters but is older – around 1 Gyr of age. Fig. 16 would indicate an age below 100 Myr for our planet. However, it is more likely that the system is older and the planet is inflated as it undergoes high insolation. Indeed, the mechanism of inflation is not taken into account in the thermal model by Fortney et al. (2007) and the planet thereby appears younger in Fig. 16 than it is from gyrochronology (120–400 Myr) and from comparison of the lithium content with stars in open clusters (27–625 Myr).

To date, the youngest known hot Jupiter planet is HIP 67522 b orbiting

the  $17 \pm 2$  Myr old G1V star (Rizzuto et al. 2020). The second youngest gas giant orbits the  $20 \pm 6$  Myr old 51 Eri star (Macintosh et al. 2015). Another candidate for a young exoplanetary system hosting gas giants is HR 8799, but the range of age estimates is large, going from 30 Myr to 1.1 Gyrs (Song et al. 2001; Marois et al. 2008; Moya et al. 2010), with a most probable solution around 155 Myrs (Sudol & Haghighipour 2012). Recently, a few more young systems were presented in Figure 18 of Benatti et al. (2021), with ages in the range of 100–400 Myr. However, TOI-2046 is still only one of the handful fully characterized exoplanetary systems of such a very young age hosting a hot Jupiter.

Finally, we would like to stress that TOI-2046b is also a good candidate for the measurement of the Rossiter-McLaughlin effect. This has an expected amplitude of 80 m/s. The measurement of the spin axis alignment for this young system may reveal more details of its evolutionary stage.

## 5 CONCLUSIONS

In this paper we present the detection and characterization of three new hot Jupiters, TOI-1181b, TOI-1516b, and TOI-2046b, which were discovered by the *TESS* space mission. We confirmed the planetary candidates by a network of instruments installed on mid-aperture sized telescopes using the *KESPRINT* consortium observing time. Two of the newly detected systems, namely TOI-1181b and TOI-1516b, are hot Jupiters with short orbital periods between 1.40–2.05 days, orbiting a G type subgiant star and a main sequence F type star, respectively. TOI-2046b, orbiting a main-sequence star, is a very young planetary system with an age between 30 and 625 Myr, making it one of the handful known systems so young. Young systems are extremely important for understanding the formation and evolution of hot Jupiters and thus further studies of this planetary system, such as an analysis of the orbital dynamics, more precise determination of its age, and perhaps also potential detection of an exo-atmosphere from space would be extremely important.

Finally, this paper clearly demonstrates that a network of telescopes with mid-sized apertures with suitable instrumentation can be used as a powerful tool for confirmation and characterization of hot Jupiter planets. Annually, about 90–135 nights of clear weather are available at Ondřejov Observatory (Kabáth et al. 2020). Observing runs aiming for characterization of giant planets are thus ideal targets for 2–4 m instruments, leaving valuable telescope time at large observatories for smaller planets.

## ACKNOWLEDGEMENTS

This work is done under the framework of the *KESPRINT* collaboration (<http://www.kesprint.science>). *KESPRINT* is an international consortium devoted to the characterization and research of exoplanets discovered with space-based missions. This work is based on data sets obtained with the Perek 2-m telescope. PK, JS, MS, RK and MB are acknowledging the support by Inter-transfer grant no LTT-20015. MK acknowledges the support from ESA-PRODEX PEA4000127913. PK and JS acknowledge a travel budget from ERASMUS+ grant 2020-1-CZ01-KA203-078200. HB’s mobility was funded under: MŠMT - CZ.02.2.69/0.0/0.0/18\_053/0016972 Podpora mezinárodní spolupráce v astronomii. PC acknowledges the generous support from Deutsche Forschungsgemeinschaft (DFG) of the grant CH 2636/1-1.

PR acknowledges support from National Science Foundations (NSF) grant No. 1952545. This work was generously supported by the Thüringer Ministerium für Wirtschaft, Wissenschaft und Digitale Gesellschaft. We acknowledge the use of public TESS data from pipelines at the TESS Science Office and at the TESS Science Processing Operations Center. Resources supporting this work were provided by the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center for the production of the SPOC data products. JIV acknowledges support of CONICYT-PFCHA/Doctorado Nacional-21191829. This work is partly supported by JSPS KAKENHI Grant Number JP20K14518. JK gratefully acknowledge the support of the Swedish National Space Agency (SNSA; DNR 2020-00104). HD acknowledges support from the Spanish Research Agency of the Ministry of Science and Innovation (AEI-MICINN) under grant PID2019-107061GB-C66, DOI: 10.13039/501100011033. R.L. acknowledges financial support from the Spanish Ministerio de Ciencia e Innovación, through project PID2019-109522GB-C52, and the Centre of Excellence "Severo Ochoa" award to the Instituto de Astrofísica de Andalucía (SEV-2017-0709). This work has made use of data from the European Space Agency (ESA) mission Gaia (<https://www.cosmos.esa.int/gaia>), processed by the Gaia Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. This is University of Texas Center for Planetary Systems Habitability contribution #0054.

LGC acknowledges support from grant FPI-SO from the Spanish Ministry of Economy and Competitiveness (MINECO) (research project SEV-2015-0548-17-2 and predoctoral contract BES-2017-082610). S. M. acknowledges support by the Spanish Ministry of Science and Innovation with the Ramon y Cajal fellowship number RYC-2015-17697 and the grant number PID2019-107187GB-I00. R. A. G. acknowledges the support from PLATO and GOLF CNES grants.

This paper includes data collected with the TESS mission, obtained from the MAST data archive at the Space Telescope Science Institute (STScI). Funding for the TESS mission is provided by the NASA Explorer Program. STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. Observations in the paper made use of the NN-EXPLORE Exoplanet and Stellar Speckle Imager (NESSI). NESSI was funded by the NASA Exoplanet Exploration Program and the NASA Ames Research Center. NESSI was built at the Ames Research Center by Steve B. Howell, Nic Scott, Elliott P. Horch, and Emmett Quigley. The authors are honored to be permitted to conduct observations on Iolkam Du'ag (Kitt Peak), a mountain within the Tohono O'odham Nation with particular significance to the Tohono O'odham people. This work is partly supported by JSPS KAKENHI Grant Number JP17H04574 and JP18H05439, JST PRESTO Grant Number JPMJPR1775, the Astrobiology Center of National Institutes of Natural Sciences (NINS) (Grant Number AB031010). This article is based on observations made with the MuSCAT2 instrument, developed by ABC, at Telescopio Carlos Sánchez operated on the island of Tenerife by the IAC in the Spanish Observatorio del Teide.

Observations in the paper made use of the High-Resolution Imaging instrument 'Alopeco. 'Alopeco was funded by the NASA Exoplanet Exploration Program and built at the NASA Ames Research Center by Steve B. Howell, Nic Scott, Elliott P. Horch, and Emmett Quigley.

'Alopeco was mounted on the Gemini North telescope of the international Gemini Observatory, a program of NSF's NOIRLab, which is managed by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation on behalf of the Gemini partnership: the National Science Foundation (United States), National Research Council (Canada), Agencia Nacional de Investigación y Desarrollo (Chile), Ministerio de Ciencia, Tecnología e Innovación (Argentina), Ministério da Ciência, Tecnologia, Inovações e Comunicações (Brazil), and Korea Astronomy and Space Science Institute (Republic of Korea).

This work was enabled by observations made from the Gemini North telescope, located within the Maunakea Science Reserve and adjacent to the summit of Maunakea. We are grateful for the privilege of observing the Universe from a place that is unique in both its astronomical quality and its cultural significance. We thank the anonymous referees for the useful suggestions to improve the paper.

## DATA AVAILABILITY

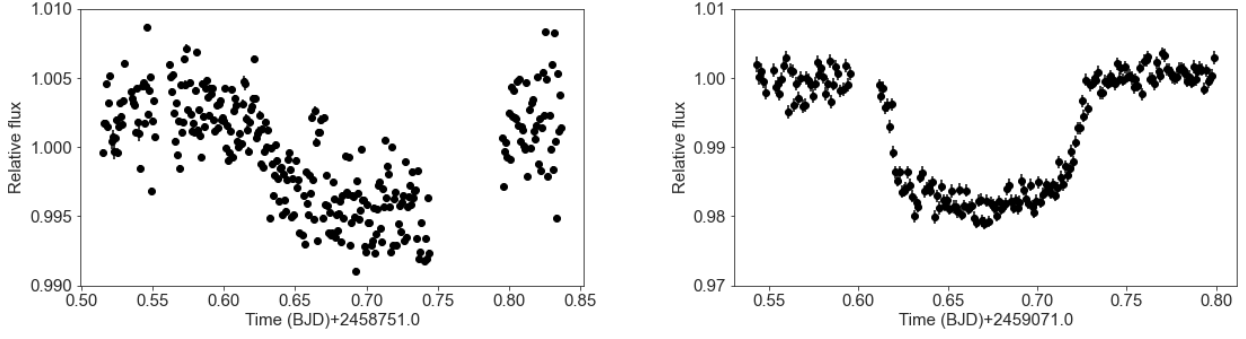
The article presents results based on data sets from the *TESS* mission, which are available at Mikulski Archive. Furthermore, the radial velocity data values are provided in the article whereas the raw and calibrated data are available upon request to the observatory archives of Tautenburg and Ondřejov and from the authors with an affiliation at the University of Texas for Tull data.

## REFERENCES

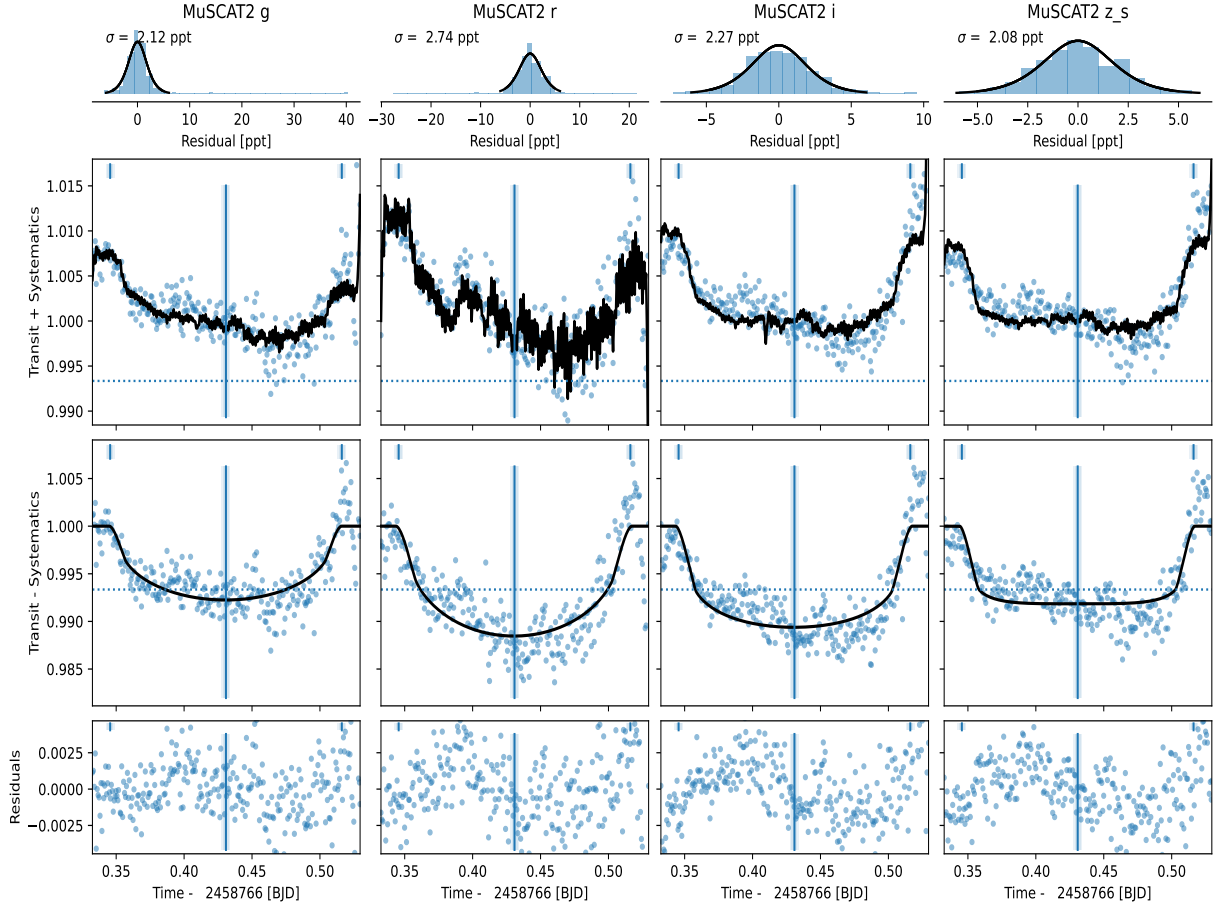
- Allard F., Homeier D., Freytag B., 2012, *Philosophical Transactions of the Royal Society of London Series A*, 370, 2765
- Anderson D. R., et al., 2011, *ApJ*, 726, L19
- Angus R., et al., 2019, *AJ*, 158, 173
- Bailer-Jones C. A. L., et al., 2013, *A&A*, 559, A74
- Barragán O., et al., 2018, *MNRAS*, 475, 1765
- Barragán O., Gandolfi D., Antoniciello G., 2019, *MNRAS*, 482, 1017
- Batygin K., Bodenheimer P. H., Laughlin G. P., 2016, *ApJ*, 829, 114
- Benatti S., et al., 2021, *A&A*, 650, A66
- Blanco-Cuaresma S., 2019, *MNRAS*, 486, 2075
- Blanco-Cuaresma S., Soubiran C., Heiter U., Jofré P., 2014, *A&A*, 569, A111
- Bluhm P., et al., 2020, *A&A*, 639, A132
- Breger M., et al., 1993, *A&A*, 271, 482
- Bressan A., Marigo P., Girardi L., Salasnich B., Dal Cero C., Rubele S., Nanni A., 2012, *MNRAS*, 427, 127
- Brown T. M., 1991, *ApJ*, 371, 396
- Butler R. P., Marcy G. W., Williams E., McCarthy C., Dosanji P., Vogt S. S., 1996, *PASP*, 108, 500
- Carleo I., et al., 2020, *AJ*, 160, 114
- Carter J. A., Winn J. N., 2009, *ApJ*, 704, 51
- Castelli F., Kurucz R. L., 2006, *A&A*, 454, 333
- Cauley P. W., Wang J., Shkolnik E. L., Ilyin I., Strassmeier K. G., Redfield S., Jensen A. G., 2021, *The Astronomical Journal*, 161, 152
- Ciardi D. R., Beichman C. A., Horch E. P., Howell S. B., 2015, *ApJ*, 805, 16
- Csizmadia S., 2020, *MNRAS*, 496, 4442
- Csizmadia S. e. a., 2021, *MNRAS*,
- Csizmadia S., Smith A. M. S., Cabrera J., Klagyivik P., Chaushev A., Lam K. W. F., 2021, arXiv e-prints, p. arXiv:2108.11822
- Döllinger M. P., Hatzes A. P., Pasquini L., Guenther E. W., Hartmann M., Girardi L., Esposito M., 2007, *A&A*, 472, 649
- Döllinger M. P., Hatzes A. P., Pasquini L., Guenther E. W., Hartmann M., Girardi L., 2009, *A&A*, 499, 935
- Dotter A., 2016, *ApJS*, 222, 8

- Eastman J. D., et al., 2019, arXiv e-prints, [p. arXiv:1907.09480](#)
- Eigmüller P., et al., 2017, *AJ*, **153**, 130
- Endl M., Cochran W. D., 2016, *PASP*, **128**, 094502
- Endl M., Kürster M., Els S., 2000, *A&A*, **362**, 585
- Esposito M., et al., 2019, *A&A*, **623**, A165
- Faigler S., Mazeh T., 2011, *MNRAS*, **415**, 3921
- Faigler S., Tal-Or L., Mazeh T., Latham D. W., Buchhave L. A., 2013, *ApJ*, **771**, 26
- Fortney J. J., Marley M. S., Barnes J. W., 2007, *ApJ*, **659**, 1661
- Frasca A., Alcalá J. M., Covino E., Catalano S., Marilli E., Paladino R., 2003, *A&A*, **405**, 149
- Fressin F., et al., 2013, *ApJ*, **766**, 81
- Fridlund M., et al., 2020, *MNRAS*, **498**, 4503
- Gaia Collaboration et al., 2016, *A&A*, **595**, A1
- Gaia Collaboration et al., 2018, *A&A*, **616**, A1
- Gandolfi D., et al., 2008, *ApJ*, **687**, 1303
- Gandolfi D., et al., 2019, *ApJ*, **876**, L24
- Gao P., et al., 2020, *Nature Astronomy*, **4**, 951
- García R. A., et al., 2011, *MNRAS*, **414**, L6
- García R. A., et al., 2014, *A&A*, **568**, A10
- Gray D. F., Brown K. I. T., 2006, *PASP*, **118**, 399
- Greene T. P., Line M. R., Montero C., Fortney J. J., Lustig-Yaeger J., Luther K., 2016, *ApJ*, **817**, 17
- Grunblatt S. K., et al., 2017, *AJ*, **154**, 254
- Grunblatt S. K., et al., 2018, *ApJ*, **861**, L5
- Grziwa S., et al., 2016, *AJ*, **152**, 132
- Guenther E. W., Hartmann M., Esposito M., Hatzes A. P., Cusano F., Gandolfi D., 2009, *A&A*, **507**, 1659
- Guerrero N. M., et al., 2021, *ApJS*, **254**, 39
- Gustafsson B., Edvardsson B., Eriksson K., Jørgensen U. G., Nordlund Å., Plez B., 2008, *A&A*, **486**, 951
- Hatzes A., Guenther E., Kürster M., 2003, in EGS - AGU - EUG Joint Assembly. EGS - AGU - EUG Joint Assembly. p. 6093
- Hauschildt P. H., Allard F., Baron E., 1999, *ApJ*, **512**, 377
- Heller R., 2019, *A&A*, **628**, A42
- Hjorth M., et al., 2019, *MNRAS*, **484**, 3522
- Howell S. B., Everett M. E., Sherry W., Horch E., Ciardi D. R., 2011, *AJ*, **142**, 19
- Howell S. B., et al., 2014, *PASP*, **126**, 398
- Huang C. X., et al., 2020a, *Research Notes of the American Astronomical Society*, **4**, 204
- Huang C. X., et al., 2020b, *Research Notes of the American Astronomical Society*, **4**, 206
- Huang C. X., et al., 2020c, *ApJ*, **892**, L7
- Husser T. O., Wende-von Berg S., Dreizler S., Homeier D., Reiners A., Barman T., Hauschildt P. H., 2013, *A&A*, **553**, A6
- Jenkins J. M., et al., 2016, in Software and Cyberinfrastructure for Astronomy IV. p. 99133E, [doi:10.1117/12.2233418](#)
- Johnson M. C., et al., 2016, *AJ*, **151**, 171
- Johnson M. C., et al., 2018, *MNRAS*, **481**, 596
- Kabáth P., Žák J., Boffin H. M. J., Ivanov V. D., Jones D., Skarka M., 2019, *PASP*, **131**, 085001
- Kabáth P., et al., 2020, *PASP*, **132**, 035002
- Kjeldsen H., Bedding T. R., 1995, *A&A*, **293**, 87
- Kreidberg L., et al., 2014, *Nature*, **505**, 69
- Kurucz R., 1993, ATLAS9 Stellar Atmosphere Programs and 2 km/s grid. Kurucz CD-ROM No. 13. Cambridge, 13
- Lenz P., Breger M., 2005, *Communications in Asteroseismology*, **146**, 53
- Li J., Tenenbaum P., Twicken J. D., Burke C. J., Jenkins J. M., Quintana E. V., Rowe J. F., Seader S. E., 2019, *PASP*, **131**, 024506
- Lightcurve Collaboration et al., 2018, Lightcurve: Kepler and TESS time series analysis in Python, Astrophysics Source Code Library ([ascl:1812.013](#))
- Luque R., et al., 2021, *A&A*, **645**, A41
- Macintosh B., et al., 2015, *Science*, **350**, 64
- Marois C., Macintosh B., Barman T., Zuckerman B., Song I., Patience J., Lafrenière D., Doyon R., 2008, *Science*, **322**, 1348
- Masuda K., Winn J. N., 2017, *AJ*, **153**, 187
- Mathur S., et al., 2010, *A&A*, **511**, A46
- Mayor M., Queloz D., 1995, *Nature*, **378**, 355
- Mentuch E., Brandeker A., van Kerkwijk M. H., Jayawardhana R., Hauschildt P. H., 2008, *ApJ*, **689**, 1127
- Morris R. L., Twicken J. D., Smith J. C., Clarke B. D., Jenkins J. M., Bryson S. T., Girouard F., Klaus T. C., 2020, Kepler Data Processing Handbook: Photometric Analysis, Kepler Science Document KSCI-19081-003
- Moya A., Amado P. J., Barrado D., García Hernández A., Aberasturi M., Montesinos B., Aceituno F., 2010, *MNRAS*, **405**, L81
- Narita N., et al., 2019, *Journal of Astronomical Telescopes, Instruments, and Systems*, **5**, 015001
- Pollack J. B., Hubickyj O., Bodenheimer P., Lissauer J. J., Podolak M., Greenzweig Y., 1996, *Icarus*, **124**, 62
- Ricker G. R., et al., 2014, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. p. 20 ([arXiv:1406.0151](#)), [doi:10.1117/12.2063489](#)
- Ricker G. R., et al., 2015, *Journal of Astronomical Telescopes, Instruments, and Systems*, **1**, 014003
- Rizzuto A. C., et al., 2020, *AJ*, **160**, 33
- Rodríguez J. E., et al., 2021, *AJ*, **161**, 194
- Sabotta S., Kabath P., Korth J., Guenther E. W., Dupkala D., Grziwa S., Klocova T., Skarka M., 2019, *MNRAS*, **489**, 2069
- Scott N. J., 2019, in AAS/Division for Extreme Solar Systems Abstracts. p. 330.15
- Shporer A., 2017, *PASP*, **129**, 072001
- Smith A. M. S., et al., 2017, *MNRAS*, **464**, 2708
- Smith A. M. S., et al., 2019, *Acta Astron.*, **69**, 135
- Soderblom D. R., Oey M. S., Johnson D. R. H., Stone R. P. S., 1990, *AJ*, **99**, 595
- Soderblom D. R., Pilachowski C. A., Fedele S. B., Jones B. F., 1993a, *AJ*, **105**, 2299
- Soderblom D. R., Fedele S. B., Jones B. F., Stauffer J. R., Prosser C. F., 1993b, *AJ*, **106**, 1080
- Song I., Caillault J. P., Barrado y Navascués D., Stauffer J. R., 2001, *ApJ*, **546**, 352
- Sudol J. J., Haghighipour N., 2012, *ApJ*, **755**, 38
- Tejada Arevalo R. A., Winn J. N., Anderson K. R., 2021, arXiv e-prints, [p. arXiv:2107.05759](#)
- Tull R. G., MacQueen P. J., Sneden C., Lambert D. L., 1995, *Publications of the Astronomical Society of the Pacific*, **107**, 251
- Twicken J. D., Clarke B. D., Bryson S. T., Tenenbaum P., Wu H., Jenkins J. M., Girouard F., Klaus T. C., 2010, in Software and Cyberinfrastructure for Astronomy. p. 774023, [doi:10.1117/12.856790](#)
- Twicken J. D., et al., 2018, *PASP*, **130**, 064502
- Valdes F., Gupta R., Rose J. A., Singh H. P., Bell D. J., 2004, *ApJS*, **152**, 251
- Van Eylen V., et al., 2016, *AJ*, **152**, 143
- Van Eylen V., et al., 2021, *MNRAS*, **507**, 2154
- Vines J., Jenkins J. e. a. i. p., 2021, *NA*,
- Wang J., Fischer D. A., Horch E. P., Huang X., 2015, *The Astrophysical Journal*, **799**, 229
- Weiss L. M., et al., 2013, *ApJ*, **768**, 14
- Weiss L. M., et al., 2017, *AJ*, **153**, 265
- Winn J. N., 2010, arXiv e-prints, [p. arXiv:1001.2010](#)
- Wong I., et al., 2020, *AJ*, **159**, 104
- Wright J. T., Upadhyay S., Marcy G. W., Fischer D. A., Ford E. B., Johnson J. A., 2009, *ApJ*, **693**, 1084
- Wytenbach A., Ehrenreich D., Lovis C., Udry S., Pepe F., 2015, *A&A*, **577**, A62
- Yan F., et al., 2021, *A&A*, **645**, A22
- Zechmeister M., Köhler J., Chamarthi S., 2021, viper: Velocity and IP Estimator ([ascl:2108.006](#))
- do Nascimento J. D. J., Canto Martins B. L., Melo C. H. F., Porto de Mello G., De Medeiros J. R., 2003, *A&A*, **405**, 723
- Šubjak J., et al., 2020, *AJ*, **159**, 151
- Žák J., Kabáth P., Boffin H. M. J., Ivanov V. D., Skarka M., 2019, *AJ*, **158**, 120
- van Dokkum P. G., 2001, *PASP*, **113**, 1420

**APPENDIX A: ADDITIONAL TABLES AND FIGURES**



**Figure A1.** Light curves of TOI-1181 (left) and TOI-1516 (right) from the CRAO Observatory.



**Figure A2.** Light curves of the transit of TOI-1181b in different filters obtained with *MUSCAT2*

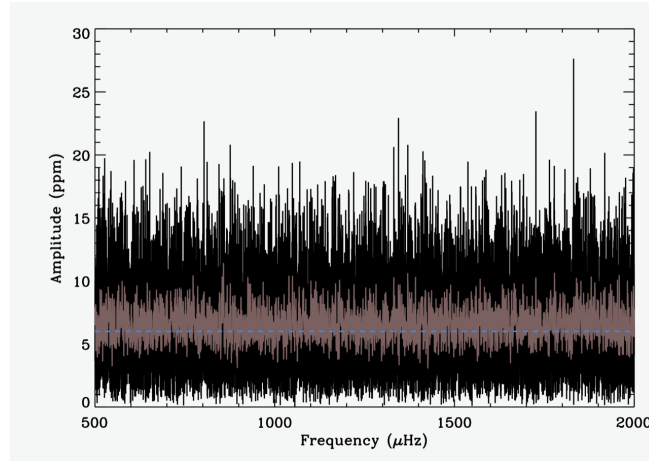
**Table A1.** Parameters determined from the *MUSCAT2* light curve for TOI-1181.

|                  |               |       |                             |
|------------------|---------------|-------|-----------------------------|
| Epoch            | 2458766.43048 | $\pm$ | 0.00054                     |
| Period           | 2.10319       | $\pm$ | 0.00001 d                   |
| Stellar density  | 0.32550       | $\pm$ | 0.00787 g/cm <sup>3</sup>   |
| Impact parameter | $b < 0.28759$ |       | (99% posterior upper limit) |
| Radius ratio     | 0.08683       | $\pm$ | 0.00132                     |



**Table A2.** Radial velocities of TOI-1181

| Date (BJD)     | RV (m/s) | $\sigma_{RV}$ (m/s) | Instrument |
|----------------|----------|---------------------|------------|
| 2458891.624504 | 119.2    | 137.2               | TCES       |
| 2458891.646611 | 135.3    | 148.6               | TCES       |
| 2458892.516390 | 244.2    | 106.3               | TCES       |
| 2458892.538323 | 82.2     | 107.6               | TCES       |
| 2458892.560290 | 210.4    | 118.0               | TCES       |
| 2458913.581137 | 99.8     | 84.3                | TCES       |
| 2458913.602628 | 127.5    | 65.5                | TCES       |
| 2458916.594736 | 176.2    | 94.2                | TCES       |
| 2458916.616264 | -1.7     | 122.9               | TCES       |
| 2458918.510222 | -113.1   | 104.0               | TCES       |
| 2458918.532270 | 130.4    | 136.5               | TCES       |
| 2458923.503219 | 252.3    | 130.6               | TCES       |
| 2458923.524388 | 246.5    | 83.3                | TCES       |
| 2459000.453694 | -13.5    | 96.6                | TCES       |
| 2459001.510255 | 222.5    | 130.5               | TCES       |
| 2459003.484689 | 303.2    | 106.1               | TCES       |
| 2459006.530164 | 186.2    | 114.4               | TCES       |
| 2459027.512966 | 83.1     | 68.2                | TCES       |
| 2459066.549074 | 232.7    | 68.3                | TCES       |
| 2459067.494285 | -7.4     | 91.5                | TCES       |
| 2459070.540453 | 304.1    | 80.3                | TCES       |
| 2459094.407467 | 188.7    | 76.3                | TCES       |
| 2459094.516228 | 221.0    | 113.7               | TCES       |
| 2459095.456436 | 96.7     | 117.3               | TCES       |
| 2459097.519515 | 68.9     | 95.2                | TCES       |
| 2459098.518832 | 196.8    | 187.3               | TCES       |
| 2459099.381413 | -31.6    | 61.8                | TCES       |
| 2459100.389551 | 438.4    | 77.1                | TCES       |
| 2459100.585164 | 322.4    | 160.9               | TCES       |
| 2459101.555221 | -49.1    | 85.7                | TCES       |
| 2459177.393867 | -142.2   | 180.3               | TCES       |
| 2459177.441483 | 13.1     | 82.7                | TCES       |
| 2459179.306668 | -130.3   | 59.4                | TCES       |
| 2459179.327816 | -30.9    | 114.0               | TCES       |
| 2459180.278832 | 180.0    | 63.5                | TCES       |
| 2459180.300000 | 208.8    | 114.9               | TCES       |
| 2459181.281956 | -113.7   | 122.3               | TCES       |
| 2459181.303683 | 519.4    | 179.6               | TCES       |
| 2459209.548487 | 231.2    | 71.8                | TCES       |
| 2459209.663867 | 130.9    | 113.6               | TCES       |
| 2459214.340952 | 82.9     | 79.5                | TCES       |
| 2459067.574725 | -89.0    | 72.0                | OES        |
| 2459070.521985 | 131.0    | 54.0                | OES        |
| 2459071.541575 | 38.0     | 70.0                | OES        |
| 2459074.598145 | 0.0      | 50.0                | OES        |
| 2459075.549465 | 182.0    | 57.0                | OES        |
| 2459086.554015 | -163.0   | 91.0                | OES        |
| 2459100.588335 | -177.0   | 91.0                | OES        |
| 2459104.572505 | -64.0    | 66.0                | OES        |
| 2458951.925755 | -136.7   | 32.9                | Tull       |
| 2458957.885446 | -21.7    | 27.8                | Tull       |
| 2458994.903263 | 163.2    | 25.0                | Tull       |
| 2459054.772528 | -114.8   | 46.2                | Tull       |
| 2459072.686735 | 138.7    | 29.8                | Tull       |
| 2459073.722383 | -117.1   | 21.6                | Tull       |
| 2459090.733304 | -124.8   | 38.8                | Tull       |
| 2459091.680828 | 98.1     | 42.1                | Tull       |
| 2459104.729921 | 115.1    | 55.3                | Tull       |



**Figure A3.** Amplitude spectrum as a function of the frequency (in black) where we superimposed a smoothed curve with an 11-point boxcar (in grey). The dash blue line corresponds to the expected amplitude of the modes of 6 ppm.

Table A3: Radial velocities of TOI-1516.

| Date (BJD)    | RV (m/s) | $\sigma_{RV}$ (m/s) | Instrument |
|---------------|----------|---------------------|------------|
| 2459209.57482 | -177     | 302                 | TCES       |
| 2459209.61444 | -821     | 179                 | TCES       |
| 2459214.38049 | -556     | 127                 | TCES       |
| 2459094.43088 | -408     | 214                 | TCES       |
| 2459095.50450 | -56      | 268                 | TCES       |
| 2459097.54374 | -417     | 209                 | TCES       |
| 2459098.54208 | -422     | 182                 | TCES       |
| 2459099.40184 | -714     | 408                 | TCES       |
| 2459099.51834 | -405     | 221                 | TCES       |
| 2459100.41467 | -291     | 81                  | TCES       |
| 2459100.60848 | -730     | 137                 | TCES       |
| 2459101.57987 | -534     | 152                 | TCES       |
| 2459177.41747 | -483     | 363                 | TCES       |
| 2459179.35048 | -611     | 300                 | TCES       |
| 2459179.37221 | -524     | 213                 | TCES       |
| 2459180.35372 | -178     | 366                 | TCES       |
| 2459180.37488 | -264     | 190                 | TCES       |
| 2459209.57482 | -177     | 302                 | TCES       |
| 2459209.61444 | -821     | 179                 | TCES       |
| 2459214.38049 | -556     | 127                 | TCES       |
| 2458863.25393 | -474     | 233                 | OES        |
| 2458864.25126 | -409     | 180                 | OES        |
| 2458865.26129 | -310     | 20                  | OES        |
| 2458872.34369 | -1054    | 191                 | OES        |
| 2458892.27580 | -604     | 90                  | OES        |
| 2458892.36445 | -568     | 110                 | OES        |
| 2458892.40691 | 193      | 123                 | OES        |
| 2458892.63805 | 298      | 152                 | OES        |
| 2458898.36529 | -179     | 130                 | OES        |
| 2458901.27357 | -764     | 92                  | OES        |
| 2458924.32249 | -867     | 105                 | OES        |
| 2458924.55897 | -915     | 128                 | OES        |
| 2458925.31019 | -165     | 43                  | OES        |
| 2458926.51850 | -478     | 60                  | OES        |
| 2458928.30224 | -1404    | 124                 | OES        |
| 2458928.47061 | -626     | 108                 | OES        |
| 2458931.27899 | 62       | 155                 | OES        |
| 2458931.56240 | 347      | 146                 | OES        |
| 2458932.30872 | -973     | 96                  | OES        |
| 2458932.60401 | -1000    | 87                  | OES        |
| 2458936.29387 | -690     | 138                 | OES        |
| 2458936.63373 | -679     | 88                  | OES        |
| 2458937.28739 | -184     | 81                  | OES        |
| 2458937.62028 | -213     | 104                 | OES        |
| 2458942.60106 | -302     | 115                 | OES        |
| 2458946.38789 | -745     | 137                 | OES        |
| 2458946.63689 | 191      | 183                 | OES        |
| 2458956.31205 | -258     | 109                 | OES        |
| 2458956.35458 | -475     | 95                  | OES        |
| 2458956.58365 | -588     | 116                 | OES        |
| 2458956.61892 | 817      | 183                 | OES        |
| 2458957.32975 | -489     | 113                 | OES        |
| 2458957.37191 | -649     | 97                  | OES        |
| 2458959.56920 | -201     | 190                 | OES        |
| 2458960.59308 | 47       | 154                 | OES        |
| 2458963.55698 | -1007    | 90                  | OES        |
| 2458963.59917 | -461     | 111                 | OES        |
| 2458976.57060 | 331      | 163                 | OES        |

Continued on next page

**Table A3 – continued from previous page**

| <b>Date (BJD)</b> | <b>RV (m/s)</b> | <b><math>\sigma_{RV}</math> (m/s)</b> | <b>Instrument</b> |
|-------------------|-----------------|---------------------------------------|-------------------|
| 2458990.55013     | 104             | 167                                   | OES               |
| 2458992.51773     | -536            | 187                                   | OES               |
| 2459101.61717     | -419            | 141                                   | OES               |
| 2459105.57857     | -419            | 139                                   | OES               |
| 2459106.57426     | -229            | 95                                    | OES               |
| 2458824.63161     | -48227          | 35                                    | Tull              |
| 2458824.77300     | -48406          | 34                                    | Tull              |
| 2459054.89122     | -48166          | 29                                    | Tull              |
| 2459072.85339     | -48318          | 28                                    | Tull              |
| 2459073.85204     | -48793          | 35                                    | Tull              |
| 2459090.80845     | -49031          | 24                                    | Tull              |
| 2459091.79470     | -48130          | 23                                    | Tull              |
| 2459104.75247     | -48831          | 42                                    | Tull              |
| 2459114.70318     | -48407          | 31                                    | Tull              |
| 2459115.79221     | -48704          | 31                                    | Tull              |
| 2459116.89061     | -48600          | 30                                    | Tull              |
| 2459133.80040     | -49039          | 36                                    | Tull              |
| 2459134.83585     | -48109          | 45                                    | Tull              |
| 2459144.76502     | -48426          | 24                                    | Tull              |
| 2459145.76340     | -48731          | 29                                    | Tull              |
| 2459171.74582     | -48147          | 11                                    | Tull              |
| 2459191.61890     | -49023          | 19                                    | Tull              |
| 2459192.65273     | -48237          | 33                                    | Tull              |
| 2459203.59849     | -49018          | 28                                    | Tull              |

This paper has been typeset from a  $\text{\LaTeX}$  file prepared by the author.

**Table A4.** Radial velocities of TOI-2046

| Date (BJD)    | RV (m/s) | $\sigma_{RV}$ (m/s) | Instrument |
|---------------|----------|---------------------|------------|
| 2459099.93401 | -237     | 10                  | Tull       |
| 2459099.94896 | -179     | 22                  | Tull       |
| 2459099.96417 | -110     | 23                  | Tull       |
| 2459100.90511 | -115     | 26                  | Tull       |
| 2459100.92022 | -125     | 21                  | Tull       |
| 2459100.93531 | -131     | 40                  | Tull       |
| 2459114.85045 | -280     | 15                  | Tull       |
| 2459115.83681 | -145     | 57                  | Tull       |
| 2459116.94014 | 355      | 41                  | Tull       |
| 2459133.87820 | -186     | 37                  | Tull       |
| 2459134.81185 | 377      | 17                  | Tull       |
| 2459143.73240 | 307      | 16                  | Tull       |
| 2459144.64706 | -405     | 33                  | Tull       |
| 2459145.69545 | 55       | 24                  | Tull       |
| 2459170.70165 | 252      | 25                  | Tull       |
| 2459171.60259 | -442     | 31                  | Tull       |
| 2459171.90490 | -75      | 21                  | Tull       |
| 2459191.64141 | 346      | 35                  | Tull       |
| 2459192.71142 | -264     | 30                  | Tull       |
| 2459202.61011 | 7        | 30                  | Tull       |
| 2459203.57473 | 314      | 18                  | Tull       |
| 2459203.82064 | 313      | 15                  | Tull       |
| 2459227.69379 | 346      | 21                  | Tull       |
| 2459240.67291 | 23       | 60                  | Tull       |
| 2459120.40138 | -656     | 171                 | OES        |
| 2459160.43763 | 528      | 119                 | OES        |
| 2459175.51402 | 258      | 213                 | OES        |
| 2459184.48565 | 841      | 94                  | OES        |
| 2459188.46491 | 547      | 129                 | OES        |
| 2459242.28485 | 1418     | 102                 | OES        |
| 2459246.27680 | 607      | 186                 | OES        |
| 2459266.25817 | 0        | 85                  | OES        |
| 2459269.31186 | 887      | 92                  | OES        |
| 2459270.27897 | 326      | 132                 | OES        |
| 2459246.26373 | -9419    | 335                 | TCES       |
| 2459266.45564 | -9047    | 142                 | TCES       |
| 2459270.52201 | -9147    | 162                 | TCES       |
| 2459271.30546 | -8563    | 206                 | TCES       |
| 2459298.29829 | -9403    | 102                 | TCES       |
| 2459299.42600 | -9237    | 151                 | TCES       |
| 2459299.55290 | -8613    | 119                 | TCES       |
| 2459300.29025 | -9705    | 167                 | TCES       |
| 2459303.32457 | -9905    | 138                 | TCES       |
| 2459303.34573 | -9958    | 232                 | TCES       |
| 2459304.32230 | -9414    | 97                  | TCES       |
| 2459304.34403 | -9478    | 121                 | TCES       |
| 2459305.31905 | -9470    | 103                 | TCES       |
| 2459305.34021 | -9538    | 153                 | TCES       |
| 2459309.32588 | -10303   | 136                 | TCES       |
| 2459309.34761 | -10030   | 163                 | TCES       |
| 2459310.39691 | -9277    | 291                 | TCES       |