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ExoClock: up-to-date ephemerides for the ARIEL mission

A. Garmash[1,2]

[1] M. A. Lavrentiev Lyceum, 10 Uchenykh St, Novosibirsk, 630068 Russia
[2] Budker Institue of Nuclear Physics, SB RAS, Novosibirsk, 630090 Russia

Abstract. Atmospheres of about 1000 exoplanets are going to be spectroscopically observed with ESA's future ARIEL mission. For the mission to be as efficient as possible, good preliminary knowledge of planet ephemerides is required before its launch, scheduled for 2029. To achieve this goal, the ExoClock project dedicated to continuous monitoring and updating the ephemerides of ARIEL candidates has been created. The project has been developed in a manner to make the best use of all available resources: observations reported in the literature, observations from space instruments, and, mainly, observations from ground-based telescopes, including both professional and amateur observatories. In this report we present our observations of exoplanet transits performed within the ExoClock project in 2022–2024.

Keywords: techniques: photometric; stars: planetary systems; astronomical databases: miscellaneous

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1 Introduction

The next big step in exoplanet studies is going to be precise measurement of the chemical composition of their atmospheres. The first attempts made by the Hubble and Webb telescopes have demonstrated the feasibility of this goal (e.g., Madhusudhan et al. 2023; Bell et al. 2023). ESA's ARIEL (Atmospheric Remote-sensing Infrared Exoplanet Large-survey) mission (Tinetti et al. 2018, 2021) is specifically dedicated to study exoplanet atmospheres. It is scheduled to launch in 2029 and is expected to spectroscopically observe about 1000 exoplanets to study their atmospheres. To achieve this goal, thousands of transits will be observed within the lifetime of the mission. This large number underlines the necessity for precise predictions of the transit times in order to maximize the overall efficiency of the mission.

Just after the discovery, the time of the next transit for a planet is well known. However, the accuracy of predicted future transits degrades over time due to the increased number of epochs since the last observation and the stacking of the period error. In extreme cases this can mean that the transit time is practically lost, having the errors of several hours. In addition, in some cases one could expect the transit times to shift due to dynamical phenomena such as tidal orbital decay or apsidal precession due to the gravitational interactions with other yet undetected bodies in the system.

These issues can only be understood and mitigated through regular long-term observations and continuous refinement of the ephemerides. In this effort, small telescopes have been proven to be as efficient as the larger ones (Zallem et al. 2020). To provide up-to-date ephemerides for the upcoming ARIEL mission, the ExoClock project has been initiated by ESA in 2019 (Kokori et al. 2022). ExoClock is an open platform with the scope of verifying, prior to the launch of the mission, the ephemerides of the planets that are going to be observed by ARIEL. Data from all available resources, including observations from space missions and ground-based facilities both professional and amateur, are to be included in the ExoClock database. ExoClock aims at providing a continuously updated and homogeneous ephemeris service which can be valuable for general exoplanet research even beyond the ARIEL mission.

As of June 2024, 380 observers from all over the world have contributed to ExoClock by submitting over 8300 observations of transits for about 620 targets.

2 Instruments, data reduction, and photometry

Most of the transit observations reported in this paper were performed in Novosibirsk, Russia, using an 11-inch Celestron Schmidt-Cassegrain telescope with an ASI2600MM camera. The filter type and exposure time for each target are given in Table 1. The `AstroImageJ` software (Collins et al. 2017) was used to process the images for the bias, dark current, and flat field corrections as well as to perform differential aperture photometry. In total, 23 transitions have been observed by the Novosibirsk group from October 2022 until July 2024. With the present equipment and average observing conditions, the seeing is usually at a level of 2″, as shown in Fig. 1a. The typical photometry accuracy for a single frame varies from 1.5 ppt for a star of 11^{m} to 8 ppt for 14^{m} with a 180 s exposure time, as shown in Fig. 1b.

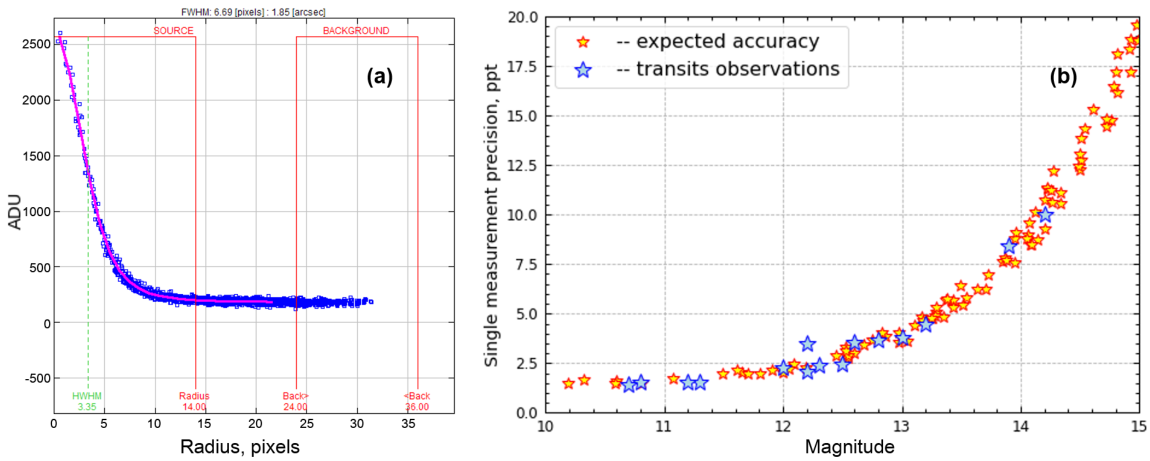

Fig. 1. (a) Typical point spread function for the present equipment and observing site. (b) The achieved standard deviation of the differential photometry measurements as a function of star magnitude with a 180 s exposer time.

3 Light curve fitting

While data reduction and photometry can be performed using tools preferred by an observer, it is of great importance to perform the final light curve modeling on the ExoClock web server to ensure maximum uniformity in the treatment of results obtained by different observers.

The final modeling of a transit is performed with the HOlomon Photometry Software package[1] (`HOPS`) specifically developed for the ExoClock project. The limb darkening coefficients (Claret et al. 2000) are calculated based on the stellar parameters (temperature, surface gravity, and metallicity) of the planet's host star as provided in

[1] https://github.com/ExoWorldsSpies/hops

Table 1. Summary of transit observations. See the ExoClock catalogue for more detail.

Target	Observing date	Filter	Exposure, s	O–C, min
HAT-P-29 b	2022-08-24	V	150	-0.62 ± 2.88
KOI-13 b	2022-08-27	V	30	-1.09 ± 2.16
HAT-P-8 b	2022-08-29	V	40	2.55 ± 1.31
WASP-3 b	2023-05-18	R	90	-1.43 ± 1.44
TrES-5 b	2023-08-01	R	200	-2.51 ± 1.58
WASP-92 b	2023-08-21	R	300	-1.87 ± 2.30
HAT-P-34 b	2023-08-29	R	60	4.52 ± 1.87
TOI-1333 b	2023-09-09	R	30	-11.66 ± 1.73
WASP-12 b	2023-10-13	R	240	-4.01 ± 1.11
WASP-52 b	2023-10-13	R	240	-1.08 ± 0.45
KELT-6 b	2024-03-18	R	120	-0.83 ± 2.16
HAT-P-12 b	2024-04-07	R	240	-0.27 ± 0.60
TOI-1842 b	2024-04-16	R	60	9.36 ± 2.74
HAT-P-27 b	2024-04-25	R	180	-1.21 ± 1.43
Qatar-10 b	2024-04-25	R	180	2.87 ± 1.31
WASP-135 b	2024-04-26	R	180	-1.79 ± 1.37
WASP-39 b	2024-04-27	R	180	0.97 ± 1.12
TOI-2154 b	2024-05-06	R	180	-3.30 ± 1.21
TOI-1431 b	2024-05-12	r'	40	0.06 ± 1.87
WASP-153 b	2024-05-13	r'	240	2.02 ± 3.46
TOI-3785 b	2024-05-15	i'	180	4.21 ± 2.02
TOI-3884 b	2024-05-16	i'	300	3.47 ± 1.30
WASP-2 b	2024-07-13	r'	180	-1.75 ± 0.65

the ExoClock catalogue[2] (ECC). During fitting, all the transit parameters except for the planet-to-star radius ratio and the transit mid-time are fixed to values from the ECC. Simultaneously with the transit model, a model for the out-of-transit effects, which are usually due to airmass variation, is applied.

An example of the fully processed data for the TOI-3884 b transit along with the model fit is shown in Fig. 2a. A similar anomaly in the photometry is apparent in the transit light curve for this target measured by TESS two years earlier, as shown in Fig. 2b. The anomaly is presumably due to a massive star spot located in a polar region of the M4 host star (Almenara et al. 2023; Libby-Roberts et al. 2023). TOI-3884 b is a super-Neptune planet that is considered as a high priority target for the study of planet atmospheres. This target is currently being monitored within the ExoClock project in an attempt to track the evolution of its transit light curve.

Besides the revision of the ephemerides, regular observation of the same target allows checking for a long-term variation of its orbital period. In some cases such

[2] ExoClock project data base: https://www.exoclock.space/database/planets

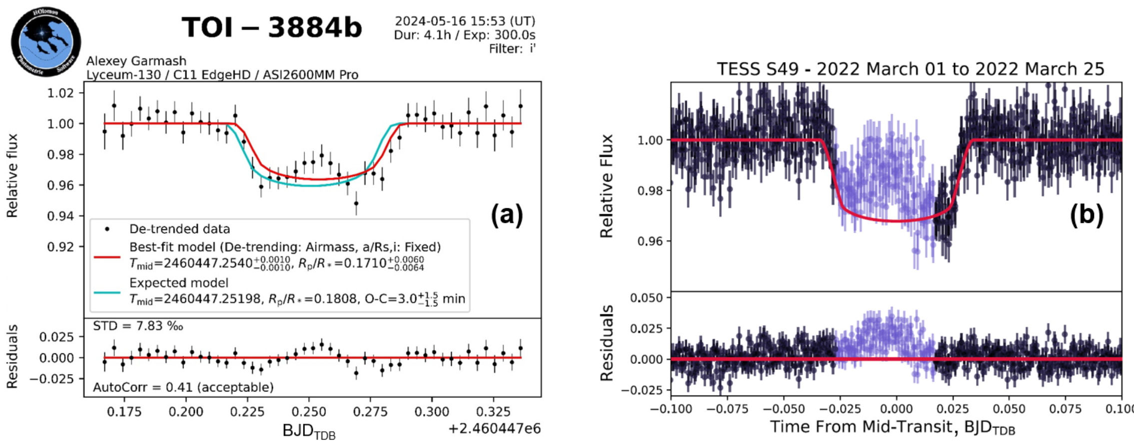

Fig. 2. (a) Example of a transit light curve measured by the Novosibirsk group for TOI-3884 b in 2024 and fitted using the `HOPS` package. (b) Transit light curve (Libby-Roberts et al. 2023) for the same target measured by TESS in 2022. A similar anomaly in the transit photometry is observed.

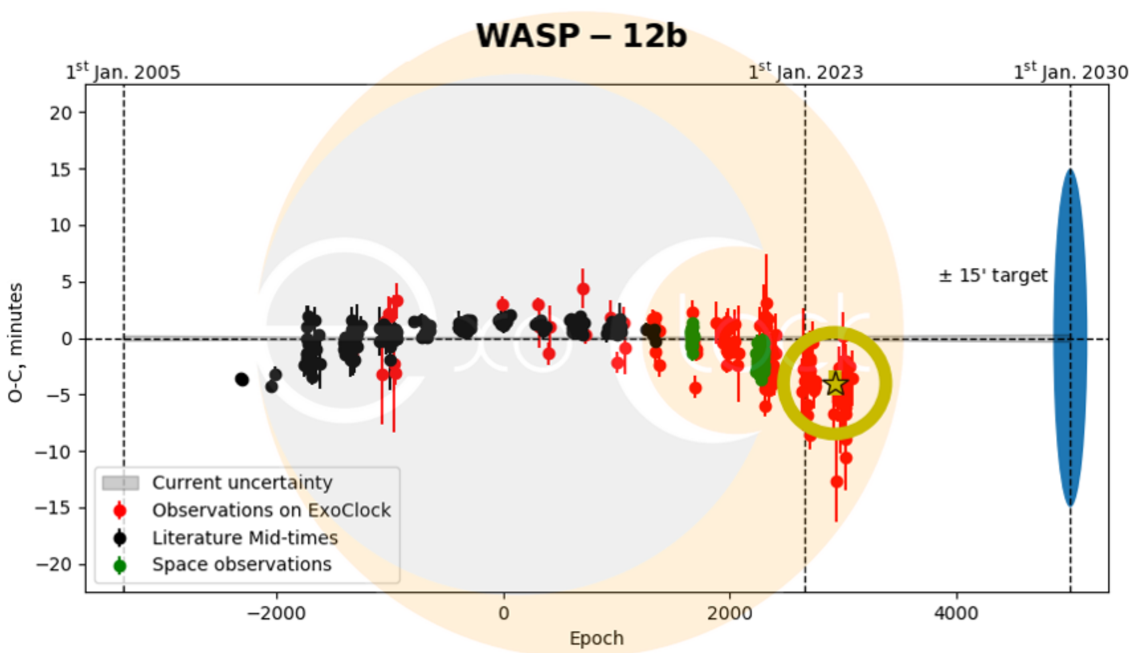

Fig. 3. O–C diagram for the exoplanet WASP-12 b from the ExoClock catalogue. The measurement from the Novosibirsk group is marked by a star symbol.

variations might indicate the presence of an additional body in the system. In the duration of the ExoClock program, 19 candidates with statistically significant transit timing variation (Kokori et al. 2023) were identified. An example of the O–C diagram (see www.exoclock.space/documents/The_OC_diagram.pdf for details) for a well known planet WASP-12 b is shown in Fig. 3. The effect was first discussed in 2019 and has been closely monitored since then by multiple ground-based telescopes as well as by the orbital TESS mission (e.g., Wong et al. 2022 and references therein). The cause of the observed variation is still under discussion with the preference given to orbit decay due to the interaction of WASP-12 b with its host star. With an orbital period of only 1.09 days and a semimajor axis of 0.023 au, there might be not only the strong tidal interaction but also mass exchange between the planet and its host star. WASP-12 b is the first and so far the only exoplanet that demonstrates the effect of orbital decay due to tidal interaction.

4 Summary

In this study we presented the transit observations of 23 exoplanets performed by the Novosibirsk group in 2022–2024 within the ExoClock project. The new measurements for transits mid-times are to be included in the upcoming ephemeris revision (Data Release D) of the ExoClock project (in preparation).

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