

DOI 10.18524/1810-4215.2022.35.268007

COMPARATIVE ANALYSIS OF OBSERVATIONS OF THE SELECTED EXOPLANET TRANSITS OBTAINED AT THE KYIV COMET STATION WITH THE DATABASE OF THE ORBITAL TELESCOPES TESS AND KEPLER

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ABSTRACT. We present a comparative analysis of observations of the selected exoplanet transits obtained at the Kyiv Comet station with the database of the TESS (Transiting Exoplanet Survey Satellite) and Kepler space telescopes. The light curves obtained by the TESS and Kepler orbital telescopes were processed using a program based on the Python package Lightcurve 2.3v which is freely available in the MUST archive (Barbara A. Mikulski Archive for Space Telescopes). The ground based observations were carried out with the 70-cm telescope AZT-8 (Lisnyky). Photometric processing of the ground based observation was performed by using the Muniwin program. The light curves and parameters of the observed transits as well as the exoplanet orbital parameters obtained from ground based observations were published in the ETD (Exoplanet Transit Database). Determined transit parameters were compared with the results of the TESS command, which are stored in the MUST archive. Here we presents a comparison of the parameters of transit phenomena (period, depth, transit duration) and some orbital parameters obtained from two independent sets of observations, terrestrial and orbital, performed in different epochs.

Keywords: transits, exoplanets, TESS, Kepler, exoplanet parameters.

АНОТАЦІЯ. Ми презентуємо порівняльний аналіз спостережень транзитів вибраних екзопланет, отриманих на кометній станції Лісники, з кривими блиску їх батьківських зір, з бази даних космічних телескопів TESS (Transiting Exoplanet Survey Satellite) і Kepler. Криві блиску, отримані орбітальними телескопами TESS і Kepler, були оброблені за допомогою програми, розробленої на основі Python пакету Lightcurve 2.3, який є у вільному доступі в архіві MUST (Barbara A.

Mikulski Archive for Space Telescopes). Спостереження також проводились на 70-ти сантиметровому телескопі-рефлекторі AZT-8 (Лісники). Фотометрична обробка цих результатів проводилась за допомогою програми Muniwin. Отримані нами з наземних спостережень криві блиску та оцінки параметрів спостережених транзитів та орбітальні параметри екзопланет опубліковані в базі даних ETD (Exoplanet Transit Database). Визначені нами параметри транзитів порівнювались з результатами команди TESS, які зберігаються в архіві MUST. В роботі представлено порівняння параметрів транзитних явищ (період, глибина, тривалість транзиту), а також орбітальних параметрів вибраних екзопланет, отриманих з двох незалежних наборів спостережень, наземних та орбітальних, виконаних в різні епохи.

Ключові слова: транзити, екзопланети, TESS, Кеплер, параметри екзопланети.

1. Introduction

There are a large number of methods for finding exoplanets. The transit method is one of the most effective. The planet covers part of the star when it passes over the disk of a star and the visible brightness falls. The time seria observed during a transit event allow us to see this fall. The magnitude of the fall in brightness depends on the relative size of the star and the planet. Therefore, the light curve provides information about the radius of the planet and some orbital parameters. But this method has several disadvantages. First, the plane of the planet's orbit should be located in such a way that we can observe the passage of the planet over the star's disk. Secondly, the planet must be large enough to be able to create a detectable drop in the star brightness. For this reason most of the planets are

found by the transit method and all the planets that we observe are hot Jupiters.

Hot Jupiters are planets with a mass of the order of the mass of Jupiter, which rotate close to their star and are always turned to it only by the one side. The period of the planet's rotation is small because they are very close to their stars. The small period allows us to observe transits regularly. Which makes hot Jupiters the most convenient targets for the observations.

The TESS and Kepler orbital telescopes conducted searches for exoplanets using the transit method. The quality of observations obtained from the orbital telescopes is definitely higher than the quality of observations obtained from ground-based telescopes. We are not hindered by various atmospheric phenomena we do not depend on the weather, time of day, phase of the Moon, etc. However, the ground based observations allow us to gather the data over large time span, which provide information about possible changes in transit parameters. The best result can be achieved by combining these two types of observations. To do this, it is necessary to determine how the results obtained from space and ground-based observations correspond to each other, and whether ground observations can be considered sufficiently accurate. The main goal of our research is to determine to what extent the parameters of exoplanets obtained from observations at the Lisnyky Comet Station coincide with the parameters obtained from observations from the TESS and Kepler orbital telescopes.

2. Observations obtained from the TESS and Kepler orbital telescopes

2.1. MAST

MAST (The Mikulski Archive for Space Telescopes) – it is an archive of data from the Webb, Hubble, TESS, Kepler space telescopes. The archive contains data from observations in the optical, ultraviolet and near-infrared ranges. The MAST archive also provides the calculated parameters (transit period, transit depth, the phase of transit event, and some orbital parameters) by the TESS and Kepler pipelines for all events surpassing some threshold. We used these published data in order to compare with the results of our ground based observations as well as with those transit parameters obtained from the Kepler and TESS light curves using our program.

2.2. TESS and Kepler missions

The TESS (Transiting Exoplanet Survey Satellite) space telescope was launched on April 19, 2018. The mission was planned for two years, during these years the telescope should examine the entire area of the sky. The celestial sphere was divided into 26 observation sectors, each sector being $24^\circ \times 96^\circ$ to detect transits of previously unknown exoplanets near the closest and brightest stars. TESS would focus on G, K, and M-type

stars with apparent magnitudes brighter than magnitude 12, and 1000 nearest red dwarfs. The rotational period of the telescope is 13.7 days. Each sector is observed for 27.4 days. The sole instrument on TESS is formed of four wide-angle CCD cameras. Each camera has a 16.8-megapixel detector with a low energy consumption and low noise, which was developed in the Laboratory of Lincoln. Each camera has a $24^\circ \times 24^\circ$ field of view, a 100 mm effective pupil diameter, a lens assembly with seven optical elements, and a bandpass range of 600 to 1000 nm.

The Kepler Orbital Telescope is NASA's space telescope designed to search for exoplanets. The telescope was launched on March 7, 2009, from the spaceport at Cape Canaveral. Kepler repeats the path of the Earth, revolving around the Sun. This arrangement allows telescope to constantly monitor one part of the sky. Kepler's field of view covers 115 square degrees near the plane of the Milky Way. The telescope has a mass of 1,039 kilograms and contains a Schmidt camera with a 0.95-meter front corrector plate feeding a 1.4-meter primary mirror. The light reflected by the mirror is collected in the main focus, where there is a mosaic of 21 pairs of specially created astronomical CCD matrices, capable of recording almost every incident photon. The dimensions of the entire mosaic are approximately 30×30 cm and it consists of 95 megapixels. These stars are located in the Orion Arm of our Galaxy, at a distance of 600 to 3000 light years. In May 2013, the telescope's second flywheel engine failed. A year after the failure of the engine, the telescope began to transmit data to Earth again. The new mission has been named K2. The telescope began to observe a section of the sky along the ecliptic. Over 9 years of operation, the telescope has discovered more than 2,680 exoplanets, 550 of which may be rocky, and 21 potentially habitable.

2.3. The data processing

The program we used to process data from the TESS and Kepler orbital telescopes was developed based on the Python package Lightcurve 2.3v, which is freely available in the MUST archive (Barbara A. Mikulski Archive for Space Telescopes).

First, the program must find data for the object we are interested in catalogs. To do this, enter the object number in the catalog, indicate exactly which mission this object was observed. The next step is the program normalizes the light curve. For several sectors, the light curves are stitched and normalized. The program finds and subtracts long-period sinusoidal oscillations, which can be star's oscillations and some kind of artifacts. The Lomb-Scargle periodogram is used for this. To detect transit events we build a periodogram, using the Box Least Squares (BLS) method. This method is much more sensitive to periodic transits. Fig. 1 present the periodogrames of star TIC236887394 from the TESS data base constructed with Lomb-Scargle

and BLS methods.

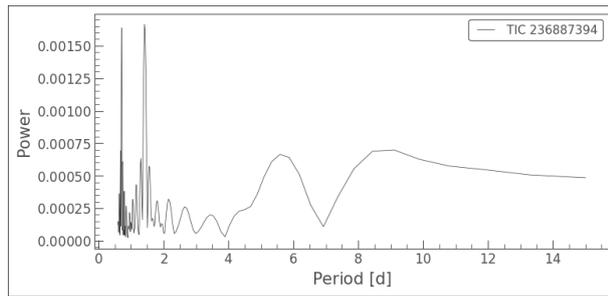


Figure 1: The Lomb-Scargle periodogram of star TIC 236887394 from the TESS data base

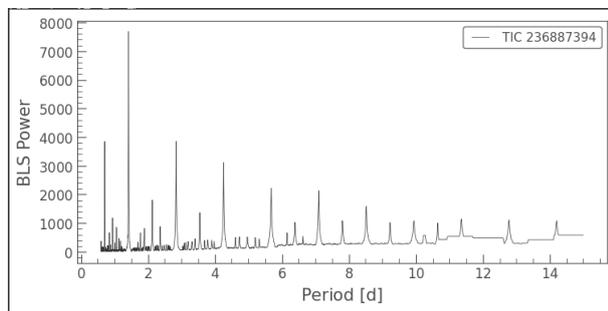


Figure 2: BLS periodogram of star TIC 236887394 from the TESS data base

The program outputs are period, duration, and first epoch of transit based on the periodogram built by the BLS method for the period at maximum power. Using these parameters we construct the folded light curve in the phase space, which helps to notice a shifts (if any) in the moments of the beginning and end of the transit. It helps to notice a shift in moments of the beginning and end of the transit. These displacements may indicate the presence of one or more planets in this system. Fig.3 demonstrates the folded phase curve for star TIC 236887394 from the TESS data base. We can see decrease in the star brightness caused by the transit event.

In order to find other possible transits we cut out parts of the light curve where the first transit occurs and repeat the procedure again building periodogram using the BLS method.

3. Observations obtained at the Lisnyky Comet Station

3.1. Observations

Observations were also carried out from March 24, 2021, to February 14, 2022, at the Lisnyky Comet Sta-

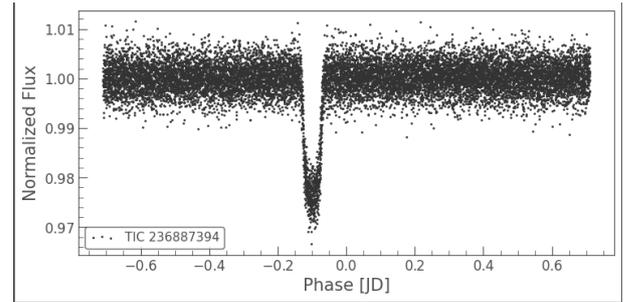


Figure 3: The folded phase curve of star TIC 236887394

tion, on the 70-centimeter AZT-8 reflector telescope, using filter R.

The telescope is equipped with a FLI PL4710 back-illuminated CCD and UBVR Bessel filters. For faint objects we use a mode with 2×2 binning, which gives a scale of 1.96/pixel. The FoV of the instrument is $16' \times 16'$ arcmin. The limiting magnitude of a 300 s exposure image is 20 mag under good sky conditions. It is possible to reach 21.5-22 mag with 1800 s exposures. For our observations, the exposure time varied from 10 to 30 seconds, depending on the brightness of the observed object.

We didn't observe one particular object all the night. We chose the star and time span for expected transit event and conducted observations during the transit only. We began shooting half an hour before the intended start time of the event and completed half an hour after the intended completion to identify possible displacements in the moments of the beginning and end of the transit.

3.2. List of observed objects and their characteristics

	Spectral type	Fluxes	Distance [pc]	Constellation
TrES-3	G	12.4	231.34	Hercules
Kepler-17	G5V	14.14	720.75	Cygnus
Qatar-1	K	12.65	185.62	Draco
WASP-43	K7V	12.08	86.75	Sextans
WASP-3	F7V	10.52	231.16	Lyra
TrES-5	K	13.77	360.31	Cygnus
Qatar-2	K5V	13.45	181.37	Virgo
WASP-10	K5V	12.03	141	Pegasus

3.3. Processing observations with Muniwin

The processing of observations obtained in the Lisnyky Comet Station was carried out using the Muniwin program. This program uses differential photometry:

Table 1: Parameters of the selected transits obtained from the ground based and orbital telescopes

Kepler 17b				
	Observation	MAST	obtained with Lightcurve 2.0	
Period [day]	1.4857108*	1.4857108	1.4856924	
Transit duration [hour]	2.41	2.29	2.40	
Depth	0.0201	1.7765[%]		
	[mag]			
Planet radius [R_j]	1.34	1.31		
Inclination [°]	90.00	87.2		
Orbital radius [AU]	0.026*	0.026		
TrES-3b				
	Observation	MAST	obtained with Lightcurve 2.0	
Period [day]	1.3061861*	1.3061858	1.3061269	
Transit duration [hour]	1.31	1.37	1.2	
Depth	0.0279	2.7361[%]		
	[mag]			
Planet radius [R_j]	1.262	1.336		
Inclination [°]	81.76	81.93		
Orbital radius [AU]	0.023*	0.023		
Qatar-1b				
	Observation	MAST	obtained with Lightcurve 2.0	
Period [day]	1.4200246*	1.4200242	1.4202261	
Transit duration [hour]	1.59	1.66	1.37	
Depth	0.0203	2.1557[%]		
	[mag]			
Planet radius [R_j]	1.093	1.143		
Inclination [°]	83.43	84.48		
Orbital radius [AU]	0.023*	0.023		
WASP-43b				
	Observation	MAST	obtained with Lightcurve 2.0	
Period [day]	0.81347414*	0.813475	0.8134242	
Transit duration [hour]	1.05	1.16	1.2	
Depth	0.0280	2.5371[%]		
	[mag]			
Planet radius [R_j]	0.93	0.93		
Inclination [°]	81.18	82.15		
Orbital radius [AU]	0.014*	0.014		
WASP-3b				
	Observation	MAST	obtained with Lightcurve 2.0	
Period [day]	1.846835*	1.846830	1.846529	
Transit duration [hour]	2.22	2.79	2.40	
Depth	0.0124[mag]	1.0269[%]		
Planet radius [R_j]	1.36	1.42		
Inclination [°]	81.71	84.15		
Orbital radius [AU]	0.0317*	0.032		

TrES-5b

	Observation	MAST	obtained with Lightcurve 2.0
Period [day]	1.48224718*	1.48224690	1.48225292
Transit duration [hour]	1.852	1.846	1.200
Depth	0.0224	2.192 [%]	
	[mag]		
Planet radius [R_j]	1.208	1.256	
Inclination [°]	84.54	84.53	
Orbital radius [AU]	0.025*	0.025	

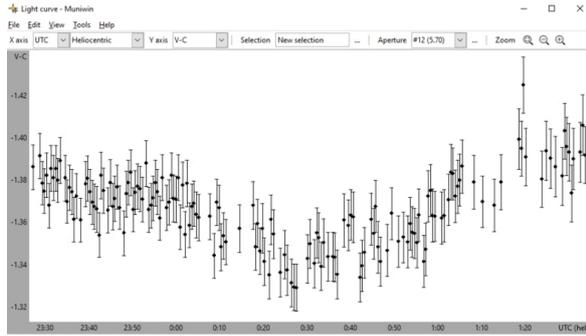


Figure 4: The light curve for the star TIC 36734222 obtained using the Muniwin program

we compare the brilliance of two or more stars. One star is one which brilliance must change due to the transit of the planet through its disk, and the other (others) are reference stars which brilliance should be unchanged. First, we calibrate the images using dark, bias, flatfield files. The next step is to set the parameters by which the program determines which object in the image is the star. The next step is to look for the corresponding stars on each image. After that, we select a star through the disk of which transit should take place and the stars which brilliance should be unchanged. Reference stars cannot be variable stars. We use the Simbad database to make sure that the selected star has constant brilliance. When the necessary stars are selected, we proceed to the light curve construction.

The resulting light curve was uploaded to the Czech Exoplanet Transit Database (ETD) for further processing.

3.4. Exoplanet Transit Database

The Exoplanet Transit Database is a Czech database. Observers can load light curves obtained from observations to this database. ETD has an algorithm for processing light curves, by which it determines the main transit parameters from these light curves: the moments of the beginning, end and middle of transit, the depth, duration and radius of the planet, and the inclination of the orbit. The period of the planet is determined from all observations pub-

lished in the database.

All our observations were uploaded to this database and received data quality 2 and 3. The data quality in the ETD is estimated on a scale from 1 to 5, where 1 is the data with the highest quality.

4. Research results

The parameters of the exoplanet transits obtained from the ground-based observations and determined from the data base of the orbital telescopes are listed in Table 1. Some of parameters we could not extract from our own observations, therefore they were taken from ETD based on all observations published in this data base. Such parameters are indicated by symbol "*". The table also comprise period and transit duration calculated in this work from the Kepler and TESS light curves.

5. Conclusion

A comparison of parameters of transit phenomena determined from two different data sets, i.e., ground-based and space-based, indicates that:

1) The transit parameters (period and duration) obtained from ground-based observations with a small telescope agree well with those obtained from Kepler and TESS orbital telescopes, highlighting the high accuracy of the ground-based observations presented in this work.

2) It is shown that the average agreement of transit parameters is at the level of 0.00001 day (transit period) and 0.1 hour (transit duration)

3) Independent processing of the light curves from the Kepler and TESS databases indicates that the preliminary processing of the light curves (detrrending, removing the long-periodic oscillations) can significantly affect the accuracy of determining the transit parameters.

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