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On the nature of the Delta Scuti star 2MASS 20061714+3818456

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This study presents a photometric analysis of the star 2MASS 20061714+3818456 based on observational data from the Maidanak Astronomical Observatory (MAO) and the Transiting Exoplanet Survey Satellite (TESS). Frequency analysis shows that the star exhibits pulsations at a fundamental frequency of $f_1 = 4.5856$ day^{-1}, which corresponds to a period of $P_1 = 0.21807465$ days, has first and second overtones. The harmonic structure and shape of the light curve indicate that the object is a Delta Scuti-type (DSCT) variable star, which exhibits short-period, small-amplitude, non-radial pulsations. A mathematical model of the stellar light curve has been developed and equations describing its periodic harmonic magnitude variation have been presented, providing further evidence for its classification as a DSCT variable.

Keywords: Stars: fundamental parameters – stars: variables: delta Scuti, oscillations

1 Introduction

The study of stellar oscillations is a powerful tool for probing the internal structures of stars by using stellar periodic oscillations (Aerts et al. 2010; Chaplin and Miglio 2013; Catelan and Smith 2015). Oscillations can be observed photometrically (Handler 2013; Aerts 2021) and pulsation frequencies can be found by calculating the power spectrum (e.g. Lomb 1976; Scargle 1982). Subsequently, many parameters such as mass, age, rotation, and distance can be measured, which is valuable as observing them is not otherwise straightforward. There are several types of stars that change their brightness as a result of pulsation, including Cepheid, Gamma Doradus, and Delta Scuti (DSCT) stars. Pulsating stars belong to the A–F spectral class, which is located on the main sequence in the Herzsprung–Russell diagram. The mass of DSCT

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stars ranges from 1.2 to 2.5 $M_{\odot}$ (solar masses), the effective temperature ($T_{\rm eff}$) is 6300–8500 K and the surface gravity of the star ($\log g$) is in the range of 3.2–4.3 (Kirmizitas and Cavus 2022). DSCT-type variable stars pulsate at frequencies between 3 day^{-1} and 80 day^{-1} in low- and medium-order pressure (p-mode), gravitational (g-mode), and mixed modes, both radial and non-radial (Uytterhoeven et al. 2011; Breger et al. 2012; Sánchez Arias et al. 2018). The g-modes carry the information of the nearcore region and the p-modes can probe the stellar envelope (Grigahcène et al. 2010; Kurtz et al. 2014; Saio et al. 2015). These oscillations provide valuable constraints on the internal structure of DSCT stars, particularly regarding energy transport processes in the transition region between the radiative core and the convective envelope (Aerts et al. 2010). Given their sensitivity to these physical processes, the pulsation properties of DSCT stars provide key observational constraints on stellar mass, age, and chemical composition, making them crucial benchmarks for intermediate mass stellar evolution models (Breger 2000; Kurtz et al. 2014). A certain class of short-period pulsating stars, Delta Scuti stars show great potential for astroseismic studies. Due to these unique characteristics, DSCT stars play a fundamental role in astroseismology, serving as crucial laboratories for probing stellar internal structure and refining our understanding of stellar evolution.

2 Observations

The star with coordinates $RA_{2000} = 20:06:17.10$ $DEC_{2000} = +38:18:45.6$ was identified as 2MASS 20061714+3818456 by the Two Micron All Sky Survey (2MASS) mission (Cutri R. M, et al., 2003). The star 2MASS 20061714+3818456 is identified in the UCAC4 star catalog with the number 642-085944 and its physical parameters are determined as follows: $B_{mag} = 14.137$ and $V_{mag} = 13.572$ in the filters (Zacharias et al. 2013), effective temperature $T_{eff} = 7403 \pm 478$ K (Bai Yu 2019), mass $M = 1.6721\,M_{\odot}$, surface gravity $\log g = 3.574$ cm/s^2 and metallicity index [Fe / H] = -0.334 (Khalatyan 2024). The map of the star region 2MASS 20061714+3818456 is shown in Figure 1.

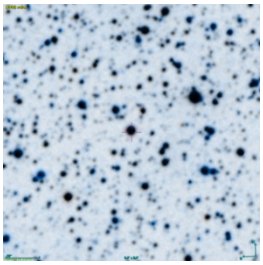


Figure 1 Field size 3.8×3.8 arc minutes, top – N (North), left – E (East), Aladin v12.0.

2.1 MAO observations

This star 2MASS 20061714+3818456 was studied from July 15 to August 6, 2023 in the area of the targeted observation of the exoplanet TOI 1168 using observations of

the Maidanak Astronomical Observatory of the Ulugbek Astronomical Institute of the Academy of Sciences of Uzbekistan (Ehgamberdiev 2018) 50 cm automated telescope with remote control AMT-1 (AstroTel-Maidanak Telescope-1) using an Apogee Alta U16M CCD matrix (4 K × 4 K). The CCD camera temperature was set at −15° C. A total of 1799 images were obtained with an exposure time of 180 seconds in filter R_C (Johnson–Cousins photometric system, filter manufactured by Astrodon). On each observation night, we obtained auxiliary flat (field), bias (zero level), and dark (dark current) images necessary for primary processing of images. The MaxIm DL 5[1] program was used to read data from the CCD camera. The AMT-1 telescope has an equatorial fork mount Mathis Instruments $MI - 750$ and optical tube of the Ritchie–Chretien system ASTROSIB $RC500$ with a focal length of 4000 mm. The physical pixel size of the Apogee Alta U16M CCD camera is 9 microns. Binning 2 × 2 was used, which corresponds to an angular pixel size is 0.907″, field of view 30.9′ × 30.9′ (Kozyreva et al. 2024).

We used the Image Reduction Analysis Facility (IRAF)[2] software packages to work with CCD images of the star 2MASS 20061714+3818456 for all steps of preliminary images processing. Preliminary photometric measurements were carried out using the VAST[3] software package, which enabled the identification and extraction of light curves from the observational data. To perform precise aperture photometry of the target star 2MASS 20061714+3818456 and selected reference stars, we utilized the DIGIPHOT/DAOPHOT/APPHOT packages within the IRAF environment. Differential photometry was then applied using constant comparison stars in the field. As a result, we obtained high-quality relative magnitudes for 2MASS 20061714+3818456, suitable for detailed time-series analysis and frequency extraction (Fig. 2).

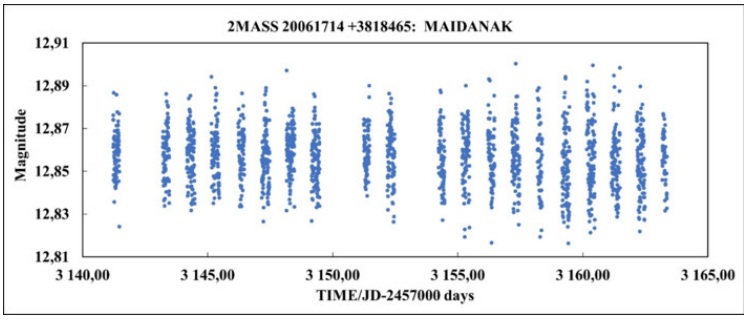


Figure 2 Overview of the light curve of the star 2MASS 20061714+3818456 based on Maidanak observations.

2.2 TESS observations

When we searched for information about the variability type and characteristics of the star 2MASS 20061714+3818456 in variable star catalogs, it turned out that no

[1]https://diffractionlimited.com/product/maxim-dl/
[2]https://ascl.net/9911.002
[3]https://scan.sai.msu.ru/vast/

information about the variability of this star was recorded. Therefore, we also used the results of photometric observation data from TESS space telescopes to determine the variability type and physical parameters of the star 2MASS 20061714+3818456. The star 2MASS 20061714+3818456 was identified as TIC 41177917 by the Transiting Exoplanet Survey Satellite (TESS) mission. Photometric data from TIC 41177917 were recorded in sectors 14, 15, 41, 54, 55, 74, 75, 81, and 82 of the TESS mission. TIC 41177917 star in sector 14 from July 18, 2019 to December 14, 2020, in sector 15 from August 15, 2019 to December 11, 2020 with 1800-second exposure times, in sector 41 from July 24, 2021 to September 21, 2022, in sector 54 from July 9, 2022 to April 11, 2023, in sector 55 from August 5, 2022 observed with 600-second exposure times until April 25, 2023, 74 sectors from January 3, 2024 to June 24, 2024, 75 sectors from January 30, 2024 to July 29, 2024, 81 sectors from July 15, 2024 to January 21, 2025, 82 sectors from August 10, 2024 to January 26, 2025 with 200-second exposure times. We downloaded the photometric data of the star TIC 41177917 in FITS format from the Mikulski Archive for Space Telescopes (MAST)[4] (Ricker et al. 2015). The determined parameters in the TESS project of the star TIC 41177917 are listed in Table 1.

Table 1 Parameters from Gaia DR3 and TESS input catalog.

Parameter	Value	Error
Plx (mas)	0.327	0.018
RUWE	0.919	
G (mag)	13.317	
B (mag)	14.137	0.032
V (mag)	13.536	0.114
TESS (mag)	12.8595	0.0225
$T_{\rm eff}$ (K)	6980	122
log g (cm/s^2)	3.4750	
Fe/H	–0.0785	
Radius ($R_\odot$)	5.40354	

We converted the photometric data of the star TIC 41177917 in FITS format downloaded from the TESS to text format using the `TOPCAT` (Taylor 2005) software. We examined the general light curves drawn using the BJD/TIME (BJD – Barycentric Julian Date) and luminous flux values of the star TIC 41177917 in all sectors in TESS and cleaned out the points that deviated from the trend. We generated its general light curve using the BJD/TIME and Detection Flux (DET_FLUX) values of the star TIC 41177917 in sector 82 (Fig. 3).

3 The frequency analysis

We determined the frequencies of variability from the MAO and TESS photometric data of the star 2MASS 20061714+3818456 using the Period04 program (Lenz and Breger 2005). To improve the Signal-to-Noise Ratio (SNR) values of the TESS observation data of the star TIC 41177917, we combined the data consisting of BJD/TIME

[4]https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html

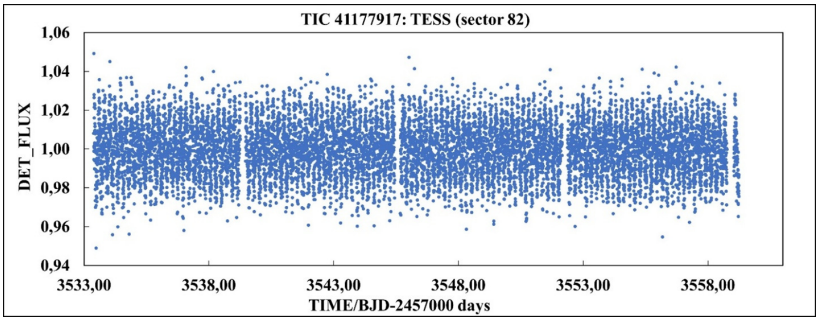


Figure 3 The overall light curve of the star TIC 41177917 in TESS.

and KSPSAP_FLUX (KSPSAP – Kepler Spline Simple Aperture Photometry) (Vanderburg 2014) and KSPSAP_FLUX_ERR values in a suitable sequence. We performed the same process for all TESS data, but the merging was done taking into account the exposure time, i.e., data with the same exposure times were merged. The combined data with equal exposure times were loaded into the Period04 program, and the Fourier transformation was performed. We also performed the Fourier decomposition in the Period04 program for the results of the photometric observation data obtained at MAO and generated the power spectrum of the star 2MASS 20061714+3818456 (TIC 41177917) (Fig. 4). This power spectrum was generated using PGRAM.[5]

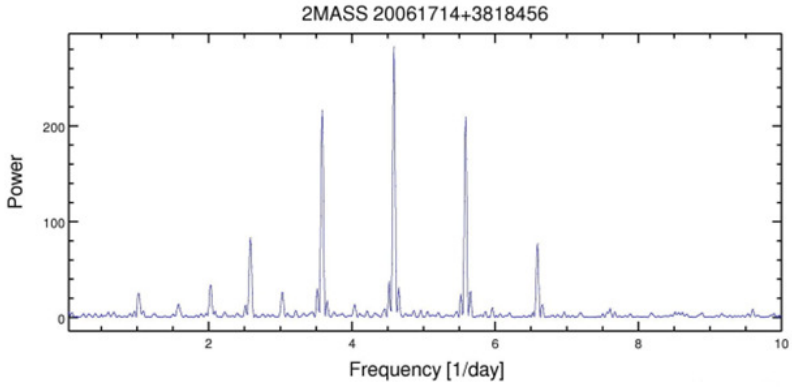


Figure 4 Power spectrum of the star 2MASS 20061714+3818456, generated from Maidanak Observatory observations. The highest peak in this graph corresponds to the frequency f_1.

The Period04 program determines the most frequently occurring active oscillation frequency in the star after the Fourier transform. To determine the next weaker oscillation frequencies, the Period04 program performs a prewhitening operation. By performing this process several times, we determined the next oscillation frequencies, amplitudes, phases and their analytical errors, and SNR values in the star. To assess

[5]https://exoplanetarchive.ipac.caltech.edu/cgi-bin/Pgram/nph-pgram

the reliability of the frequencies, Breger et al. (1993) used a signal-to-noise ratio (SNR) threshold of 4, while Baran et al. (2015) set their SNR threshold at 5. Taking into account the findings of these authors, we determined that frequencies with an SNR value below 4.5 are deemed insignificant (Table 2).

Table 2 Oscillation frequencies, amplitudes, phases, and their analytical errors and SNR values of the star 2MASS 20061714+3818456 based on the results of MAO and TESS photometric observation data.

Maidanak Astronomical Observatory (MAO)

Frequency (day^{-1})	Amplitude (mmag)	Phase (rad)	SNR
$f_1 = 4.5856 \pm 0.0005$	17.5 ± 0.3	0.918 ± 0.003	7.02
$f_2 = 5.5863 \pm 0.0009$	9.6 ± 0.3	0.241 ± 0.006	7.04
$f_3 = 6.589 \pm 0.003$	2.3 ± 0.3	0.095 ± 0.024	5.75
$f_4 = 3.5849 \pm 0.0006$	14.9 ± 0.3	0.783 ± 0.003	6.31
$f_5 = 2.581 \pm 0.001$	6.9 ± 0.3	0.874 ± 0.008	4.70

Transiting Exoplanet Survey Satellite (TESS), 14 and 15 sectors

Frequency (day^{-1})	Amplitude (mmag)	Phase (rad)	SNR
$f_1 = 4.5855 \pm 0.0006$	3.2 ± 0.2	0.081 ± 0.008	10.41
$f_2 = 6.1899 \pm 0.0009$	1.8 ± 0.2	0.340 ± 0.010	7.43
$f_3 = 1.576 \pm 0.001$	1.2 ± 0.2	0.250 ± 0.020	4.66

TESS: Sectors 41, 54, and 55

Frequency (day^{-1})	Amplitude (mmag)	Phase (rad)	SNR
$f_1 = 4.58605 \pm 0.00002$	5.8 ± 0.9	0.084 ± 0.002	24.44
$f_2 = 7.5841 \pm 0.0001$	1.0 ± 0.9	0.828 ± 0.015	7.64
$f_3 = 6.1894 \pm 0.00007$	1.7 ± 0.9	0.325 ± 0.008	10.88
$f_4 = 1.5744 \pm 0.0001$	1.1 ± 0.9	0.856 ± 0.013	7.25

TESS: Sectors 74, 75, 81, and 82

Frequency (day^{-1})	Amplitude (mmag)	Phase (rad)	SNR
$f_1 = 4.58639 \pm 0.00002$	12.2 ± 0.1	0.758 ± 0.001	20.13
$f_2 = 7.5841 \pm 0.0002$	1.1 ± 0.1	0.748 ± 0.016	5.11
$f_3 = 9.1727 \pm 0.0002$	1.0 ± 0.1	0.452 ± 0.016	6.52

The pulsation frequency $f_1 = 4.585$ day^{-1} of the star 2MASS 20061714+3818456 shows the same result in all sectors of the MAO and TESS observations (Table 2). It can be seen that the star 2MASS 20061714+3818456 pulsates at a single fundamental frequency $f_1 = 4.585$ day^{-1} with a period of $P_1 = 0.21807$ days. This pulsation period of $P_1 = 0.21807$ days is within the range of pulsation periods of Delta Scuti-type variable stars (Breger 1979). The frequency $f_5 = 2.581$ day^{-1} in MAO observations, the frequency $f_3 = 1.576$ day^{-1} in TESS observations in sectors 14, 15, and the frequency $f_4 = 1.5744$ day^{-1} in sectors 41, 54, and 55 are located outside the range of pulsation frequencies of Delta Scuti-type stars. The value $f_3 = 2 \times f_1$, calculated from the results of photometric data from the TESS project in sectors 74, 75, 81 and 82 of the star 2MASS 20061714+3818456, is twice as large as the value of f_1 determined in these same sectors. The remaining frequencies, the values of which are given in Table 2, are also located outside the range of pulsation frequencies of Delta Scuti-type stars, and their contribution to the stellar pulsation is smaller.

4 Discussion

The total observation time at MAO is 17.18 times longer than the period of the star's pulsation and brightness change, $P_1 = 0.21807$ days, and it is sufficient to determine the variability period of the star 2MASS 20061714+3818456. Using the photometric results of the MAO and TESS observations, we draw a light curve for the star 2MASS 20061714+3818456 with a pulsation frequency of $f_1 = 4.585$ day^{-1} or a period of $P_1 = 0.21807$ days. To do this, we converted the DET_FLUX values in TESS sector 82 to stellar magnitudes using the TESS mag values in Table 1 (Fig. 5).

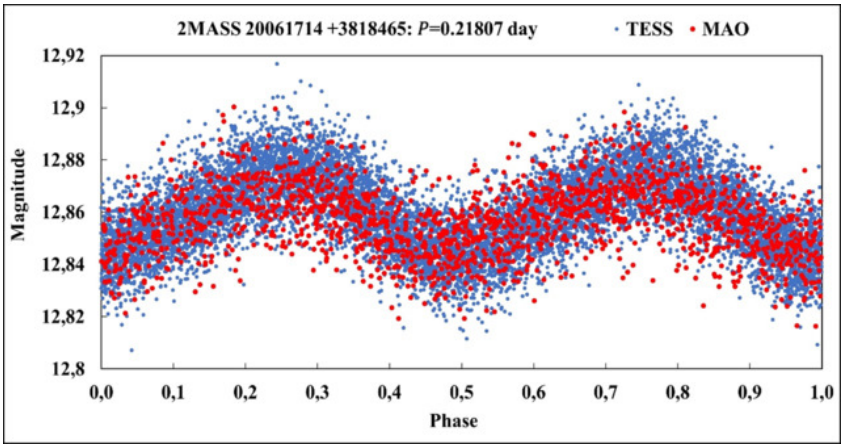


Figure 5 Light curve of the star 2MASS 20061714+3818456, MAO - red, TESS - blue dots. The light curve is shown in 2 × P (P, period) in phase 0–1.

The constant imbalance between the gravitational $\vec{F}_G$ and turbulent pressure $\vec{F}_P$ forces in the inner layers of a star causes a temperature difference in the star's inner layers, which creates thermal motion. Pulsations can occur due to thermal motion in the inner layers of a star. The excitation of pulsations in DSCT stars is primarily driven by three mechanisms: the k (kappa) mechanism operating in the He II ionization zone (Chevalier 1971; Breger 2000), turbulent pressure in the hydrogen ionization region (Antoci et al. 2014), and the edge-bump mechanism (Stellingwerf 1979; Murphy et al. 2020). These driving mechanisms, along with stellar evolution, rotation, and binarity, collectively influence the observed pulsation frequencies and amplitudes. These pulsations involve particles in the inner layers of the star in a continuous harmonic and unharmonic oscillatory motion. Their effect can cause small changes in the star's surface, deviating from its spherical shape. The wide shape of the light curve, which is formed because of the large number of observation points from MAO and TESS, indicates that the pulsations in the star occur radially (Fig. 5). The shape of the light curves formed as a result of the pulsations of most Delta Scuti-type variable stars is expressed as sinusoidal or cosinusoidal harmonic laws as follows:

$$x(t) = A \sin(2\pi f t + \varphi).$$

Here A is the amplitude, f is the frequency, φ is the phase and t is the time. The shape of the light curve formed by the pulsation of the star 2MASS 20061714+3818456 is also formed on the basis of harmonic laws. Based on harmonic laws, the periodic change in the relative magnitude of the star 2MASS 20061714+3818456 can be expressed as

$$m(t) = m_0 + A \sin(2\pi f t + \varphi),$$

where m_0 is the apparent magnitude of the star in the absence of pulsation, A is the amplitude of the change in the magnitude of the star, f is the pulsation frequency of the star, φ is the pulsation phase, and t is time.

5 Conclusion

The variability type and period of the star 2MASS 20061714+3818456, have not been recorded in the catalogs of variable stars to date. After analyzing the results of the MAO and TESS photometric observation data of star 2MASS 20061714 + 3818456 and studying them in detail, we have determined that this star pulsates with a frequency of $f_1 = 4.585$ day^{-1} or a period of $P_1 = 0.21807$ days. We determined first and second overtones.The parameters we determined in the framework of this work and the harmonic shape of the light curve shown in Figure 5 demonstrate characteristics typical of Delta Scuti-type variable stars, which periodically change their brightness as a result of pulsation. According to our research results based on the analysis of the causes of pulsation occurring in the inner layers of the star, the harmonic shape of the light curve formed as a result of pulsation, and the pulsation frequency, the star 2MASS 20061714+3818456 is a short-period, small-amplitude, non-radial pulsating variable star of the Delta Scuti (DSCT) type. Light curve shown in Fig. 5 of the star 2MASS 20061714+3818456 can be quite accurately described by the periodic harmonic change in the stellar magnitude of the star.

Acknowledgments

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