COMMISSIONS G1 AND G4 OF THE IAU
INFORMATION BULLETIN ON VARIABLE STARS

Volume 63 Number 6264 DOI: 10.22444/IBVS.6264

Konkoly Observatory
Budapest
25 April 2019

*HU ISSN 0374 – 0676*

# A NEW VARIABLE IN THE FIELD OF WD1145+017

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**Abstract**

Revisit of the CCD archive obtained during long-time monitoring of the white dwarf WD1145+015 at Tien-Shan Observatory revealed a new variable star, identified as Gaia DR2 3796400796427214848. It was inferred that this star is of spectral type G7V-G8V. The amount of photometric data allows performing detailed analysis of this target, revealing its rotational-modulation variability. The period of variation is 6.33 h which makes this star an ultra-fast rotator. The stability of variability might be due to "magnetic saturation" of the angular momentum loss. Yet another possible interpretation of the brightness variation is an elliptical variable binary system.

## 1 Introduction

The field around WD1145+017 has been continuously monitored at Tien-Shan Observatory (TSO, Kazakhstan) since 2016. Recently, we developed a new code for automatic processing and PSF-photometry of all targets on the CCD frames (Serebryanskiy et al., 2018). This code is based on the IRAF[1] realization in `python` (`pyraf`), `astropy`[2] library, `scamp` (Bertin, 2006), `astroquery`, to name just a few. Using this code a new variable was found while processing CCD-images of the field of WD1145+017 obtained in 2016-2018.

## 2 Observations

The field around WD1145+017 was observed during 2016-2018 at TSO using the "Zeiss-1000" telescope equipped with an Apogee Alta U9000 CCD camera using a Kodak KAF-09000 chip with 3056×3056 pixels and 12 $\mu$m pixel size. Equivalent focus length of the "Zeiss-1000" is 6665.0 mm using a specially designed focus reducer and field corrector which provide $19' \times 19'$ FOV with a scale of $0''.37$/px. To improve the SNR, observations were performed in 2×2 binning which reduce resolution to $0''.75$/px. The cadence of the observations was 40, 60 and 90 sec depending on the filter. More information about observation is provided in Table 1. The new variable, identified as Gaia DR2 3796400796427214848, and WD1145+017 are indicated in the finding chart given in Figure 1.

[1]Image Reduction and Analysis Facility, http://iraf.noao.edu

[2]This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration, 2018)

Table 1: Log of observations.

| Date | BJD interval 2457451+ | Duration [hours] | Number of frames | Filter | Exposure [sec] |
|---|---|---|---|---|---|
| 03.03.2016 | 0.170767 − 0.478716 | 7.39 | 351 | Johnson $R$ | 60 |
| 04.03.2016 | 1.178087 − 1.485414 | 7.38 | 350 | Johnson $R$ | 60 |
| 05.03.2016 | 2.208392 − 2.482231 | 6.57 | 312 | Johnson $R$ | 60 |
| 06.03.2016 | 3.164791 − 3.480801 | 7.58 | 338 | Johnson $R$ | 60 |
| 08.03.2016 | 5.241870 − 5.463236 | 5.31 | 253 | clear | 60 |
| 09.03.2016 | 6.198473 − 6.452463 | 6.10 | 288 | clear | 60 |
| 14.04.2016 | 42.115488 − 42.329463 | 5.14 | 233 | clear | 60 |
| 23.04.2016 | 51.240633 − 51.355715 | 2.76 | 130 | Johnson $R$ | 60 |
| 26.02.2017 | 360.208351 − 360.519519 | 7.47 | 382 | clear | 60 |
| 03.07.2017 | 369.304570 − 369.395335 | 2.18 | 70 | Johnson $V$ | 90 |
| 14.04.2017 | 407.108791 − 407.312858 | 4.90 | 151 | Johnson $V$ | 90 |
| 07.05.2018 | 795.139439 − 795.306060 | 4.00 | 233 | clear | 40 |

Light curves for all stars on the field were computed using the systematics removal algorithm by Tamuz et al. (2005). The light curve for the new variable star is shown in Figure 2 and reveal the presence of variability with a period of several hours. This new variable is not listed either in the Simbad Database or in the General Catalogue of Variable Stars.

Querying Gaia Data Release 2 (Gaia Collaboration, 2018) reveals the following parameters for this object: RA(J2000)=11:48:47.79, DEC(J2000)=+01:23:39.4, $G = 16.2725 \pm 0.0020$ mag, $G_{\rm BP} = 16.7102 \pm 0.0104$ mag, $G_{\rm RP} = 15.6506 \pm 0.0068$ mag, parallax $\pi = 0.6594 \pm 0.1032$ mas, $T_{\rm eff} = 5149.17^{+94}_{-102}$ K.

## 3 Light curve analysis

Using the light curves from individual nights two merged light curves were compiled: 1) the "long" one using all light curves and 2) "short" one using light curves for 2016 only. Then, the period search was performed using the Generalized Lomb-Scargle algorithm realized in `gatspy` (VanderPlas et al., 2015) and Phase Dispersion Minimization (`PyAstronomy`). The necessity to use a "short" merged light curve is dictated by several reasons: 1) to avoid the long duration gap in the data, 2) to avoid possible period variations. The corresponding frequency spectra are shown in Figures 3 and 4. The periods found are presented in Tables 2 and 3.

Table 2: Periods estimated using the "long" merged light curve.

| Mode | $f$ c/d | $\sigma_f$ c/d |
|---|---|---|
| f1 | $3.788^a$, $3.789^b$ | 0.01 |
| f2 | $7.576^a$, $7.576^b$ | 0.01 |

$^a$ - GLS, $^b$ - PDM

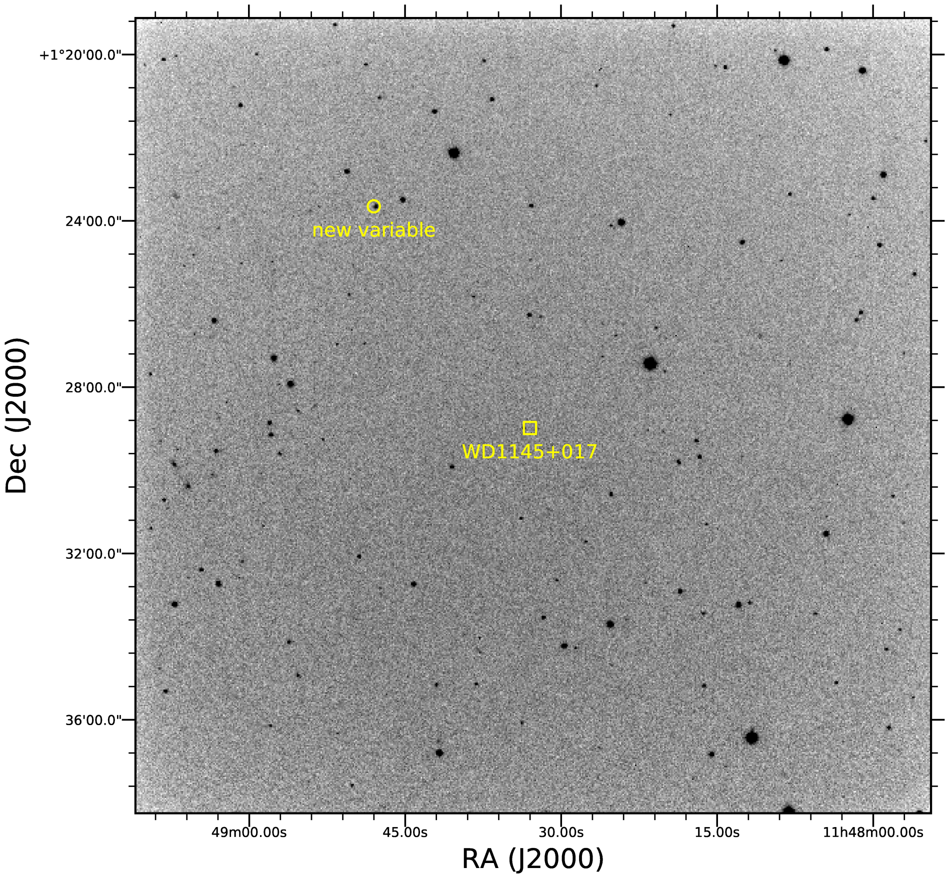


**Figure 1.** Finding chart of the field around WD1145+017,with the new variable, Gaia DR2 3796400796427214848, indicated.

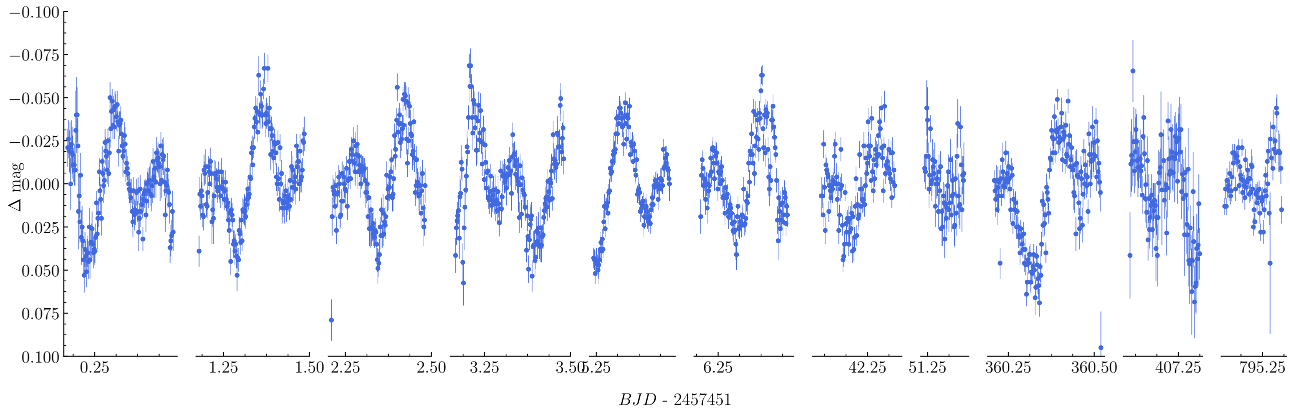


**Figure 2.** Light curves of the new variable in the field of WD1145+017.

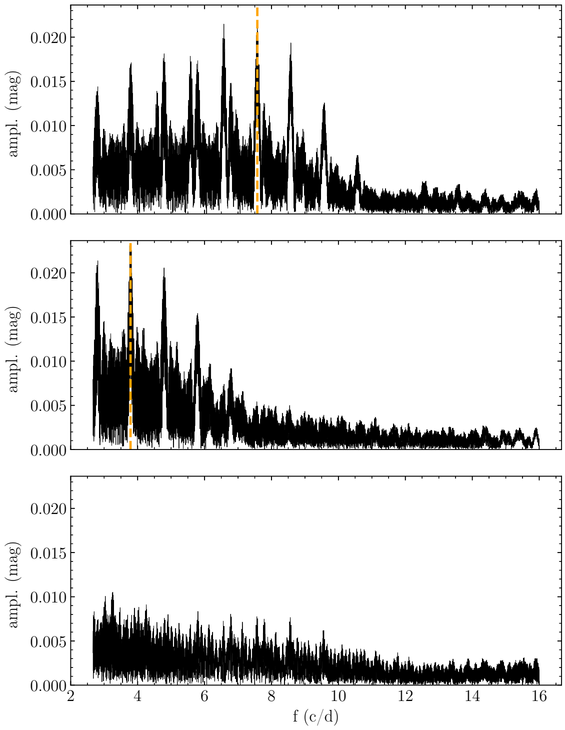


**Figure 3.** GLS frequency spectrum using the "long" merged light curve with the found periodicity indicated.

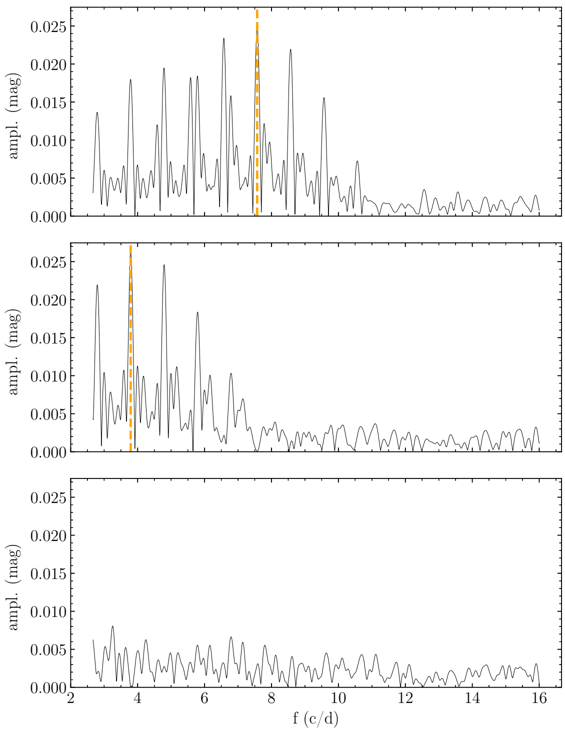


**Figure 4.** GLS frequency spectrum using the "short" merged light curve with the found periodicity indicated.

Table 3: Periods estimated using the "short" merged light curve.

| Mode | $f$ c/d | $\sigma_f$ c/d |
|---|---|---|
| f1 | $3.793^a$, $3.789^b$ | 0.01 |
| f2 | $7.572^a$, $7.577^b$ | 0.01 |

$^a$ - GLS, $^b$ - PDM

The main period is ≈6.33 h, and the second period is almost exactly half of the main one which might be an indication that this is rotation modulated variability. To check this assumption and to determine other parameters of the modes the light curves for individual nights were fitted using Equation (1) with fixed $\Pi_1$ parameter and five free parameters: $A_0, A_1, A_2, \phi_1, \phi_2$.

$$y_{fit} = A_0 + A_1 \sin(2\pi(t - \phi_1)/\Pi_1/2) + A_2 \cos(2\pi(t - \phi_2)/(\Pi_1)) \quad (1)$$

Examples of the fitting results are shown in Figure 5 and Figure 6 for two different epochs of observations.

The figures show that the second period is indeed half of the first one and the period of the first variation is stable. The amplitudes of the two modes are shown in Figure 7. This indicates that we are dealing with rotational modulation variability.

The two phases, $\phi_1$ and $\phi_2$, and the constant period $\Pi_1$ were used to compute the O–C diagram shown in Figure 8. The O–C diagram was fitted using Equation (2). The observed O–C diagram for two phases and corresponding fitting results are shown in Figure 8.

$$(O - C) = \Delta E_0 + P \cdot E + \frac{1}{2} P \cdot \frac{dP}{dt} \cdot E^2 \quad (2)$$

From O–C fitting it was found that for the first harmonic (phase $\phi_1$) $\dot{P}_1$ = (-4.3 ± 0.4) × 10 $^{-6}$ d y$^{-1}$, for the second harmonic (phase $\phi_2$) $\dot{P}_2$ = (76.0 ± 3.0) × 10 $^{-6}$ dy$^{-1}$.

## 3.1 Interpretation

To interpret the variability and evolutionary status of this new variable I first estimated the color index $(B-V)$ of this star from our multicolor photometry obtained on May 13, 2017. The results are: $(B - V) = 0.713 \pm 0.04$ mag, $(V - R) = 0.365 \pm 0.02$ mag. The color excess from Edge et al. (2013) is E$(B - V)$ = 0.0220 mag.

Moreover, using the value for $T_{\rm eff}$ and results of Eker et al. (2015) one can find that $\log(M/M_\odot) \approx -0.1$, $\log(L/L_\odot) \approx -0.5$, and $\log(R/R_\odot) \approx -0.1$. From Table 3 by Miller (2015), we get [Fe/H] ≈ -0.580, with $\rho = 0.0756$.

The location of this star in the color-magnitude diagram is shown in Figure 9. I used a 4×4 degree area around the target to build this diagram. Based on this information I conclude that this star is of spectral type G7V-G8V. Considering its proper motion ($\mu_\alpha$ = −3.9 mas/y, $\mu_\delta$ = −9.4 mas/y) and distance ($\pi$ ∼ 0.7 mas) I estimated the components of space velocity of this target: (U,V,W) = 7 km s$^{-1}$, –75 km s$^{-1}$, –20 km s$^{-1}$. Since there is no information on radial velocity for this star in these catalogs I used

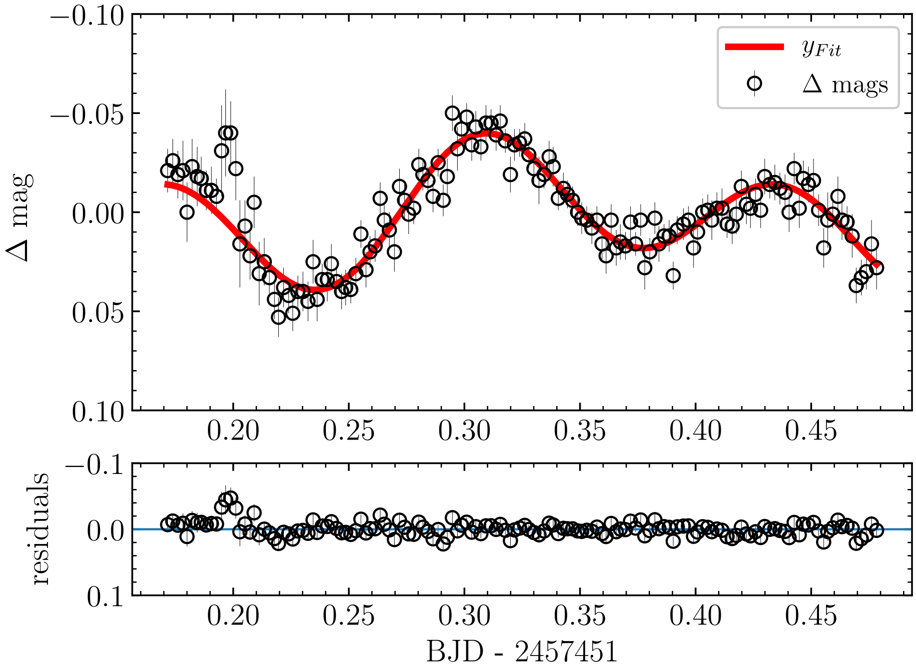


**Figure 5.** Top: the light curve of the new variable observed on 03.03.2016 (open circles) and fit results using Equation (1) (solid red line). Bottom: residual.

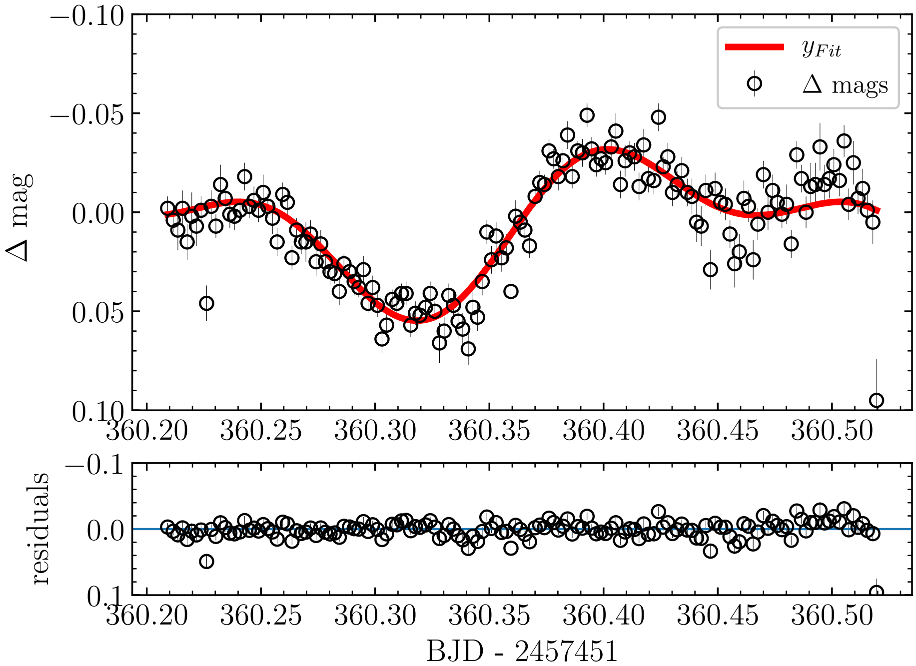


**Figure 6.** Top: the light curve of the new variable observed on 26.02.2017 (open circles) and fit results using Equation (1) (solid red line). Bottom: residual.

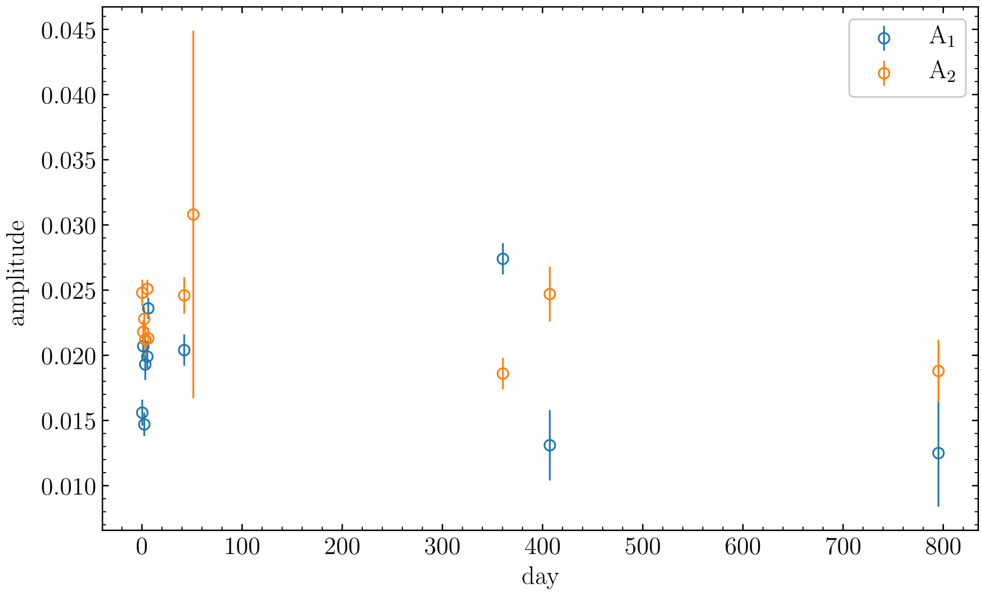


**Figure 7.** Amplitudes $A_1$ and $A_2$ determined from fitting Equation (1) to individual light curve as a function of epoch of observation

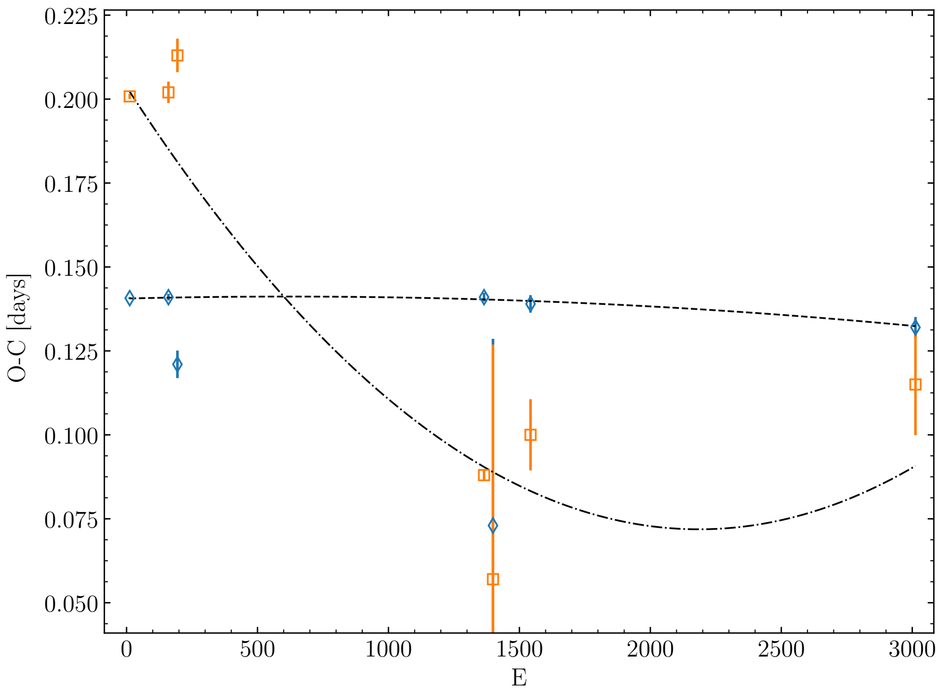


**Figure 8.** O–C computed from $\phi_1$ (blue symbols) and $\phi_2$ (red symbols) as a function of epoch E. Dashed lines are results of fitting using Equation (2).

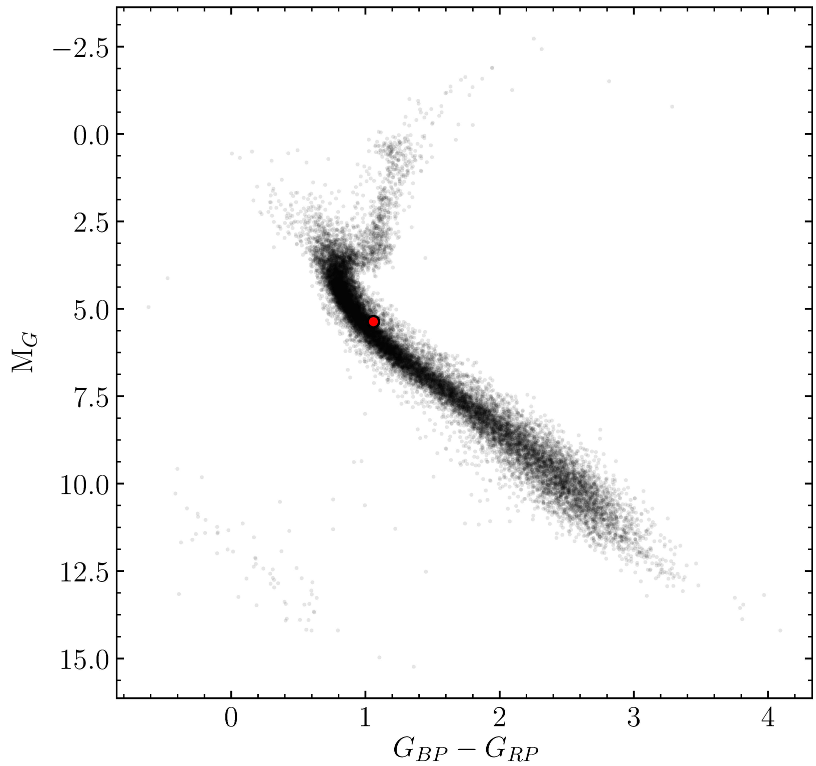


**Figure 9.** Color-magnitude diagram from Gaia Data Release 2 (Gaia Collaboration, 2018) for the stars in the field 4×4 degrees around the new variable star indicated by red symbol.

results from Sperauskas et al. (2016). The kinematics and metallicity indicate that this star belongs to Galactic disk.

If we assume that variability is caused by rotational modulation by a stellar spot then the period of 6.33 h and the radius of the star imply that this star is ultra-fast rotator ($\sim$ 190 km s$^{-1}$) which is usually an indication of young age. The possible explanation of existence of such fast rotators may be given by "magnetic saturation" of the angular momentum loss during evolution of the star and dependence of the saturation process on stellar mass.

To explain the amplitude and coherence of the variability the star spot area should be quite large and stable. It is known that bigger sports for cooler stars survive longer. But, as one can deduce using Equation (8) of (Giles et al., 2017) for r.m.s. = 0.016 and $T_{\rm eff}$=5100 K for our target gives us $\tau_{AR} \approx 200$ days which is confirmed by Figure 8 from the same work for G stars. This is as twice as shorter than observed stability (amplitude and phase) in our case.

This leads us to another (less possible) interpretation - semidetached binary system of ellipsoidal variation. To model this system I used "nightfall"[3] with a fixed period of rotation being 0.2640 days and fixed $T_{\rm eff}$ = 5100 K of the primary. I also fixed the mass of the primary to $M_{\rm prim}$ = 0.796 M$\odot$. I assume that the primary is filled its Roche lobe and has synchronous rotation while secondary one is below the Roche lob and rotates asynchronous with factor $\sim$ 10.

The folded light curves for two filters and the modeled light curves are shown in Figure 10. The physical parameters of the system from the best fit "nightfall" modeling are

[3] https://www.hs.uni-hamburg.de/DE/Ins/Per/Wichmann/Nightfall.html

Table 4: Estimated system parameters from "nightfall" modeling.

| $T_{\rm eff}^{\rm prim}$ | $T_{\rm eff}^{\rm sec}$ | $M_{\rm prim}$ $(M/M\odot)$ | $M_{\rm sec}$ $(M/M\odot)$ | $i$ | $\Omega$ | e |
|---|---|---|---|---|---|---|
| 5100 K | 12170 K | 0.796 | 0.524 | 49.64 | 64.20 | 0.047 |

shown in Table 4. I should note that this system is not an eclipsing but elliptical variable (see Figure 11 for a vizualization of the system configuration at different phases).

The period of rotation 0.2640 d is below the short limit for contact and semidetached binaries of 0.22 d.

We plan to observe this system in February-March of 2019 both photometrically and spec

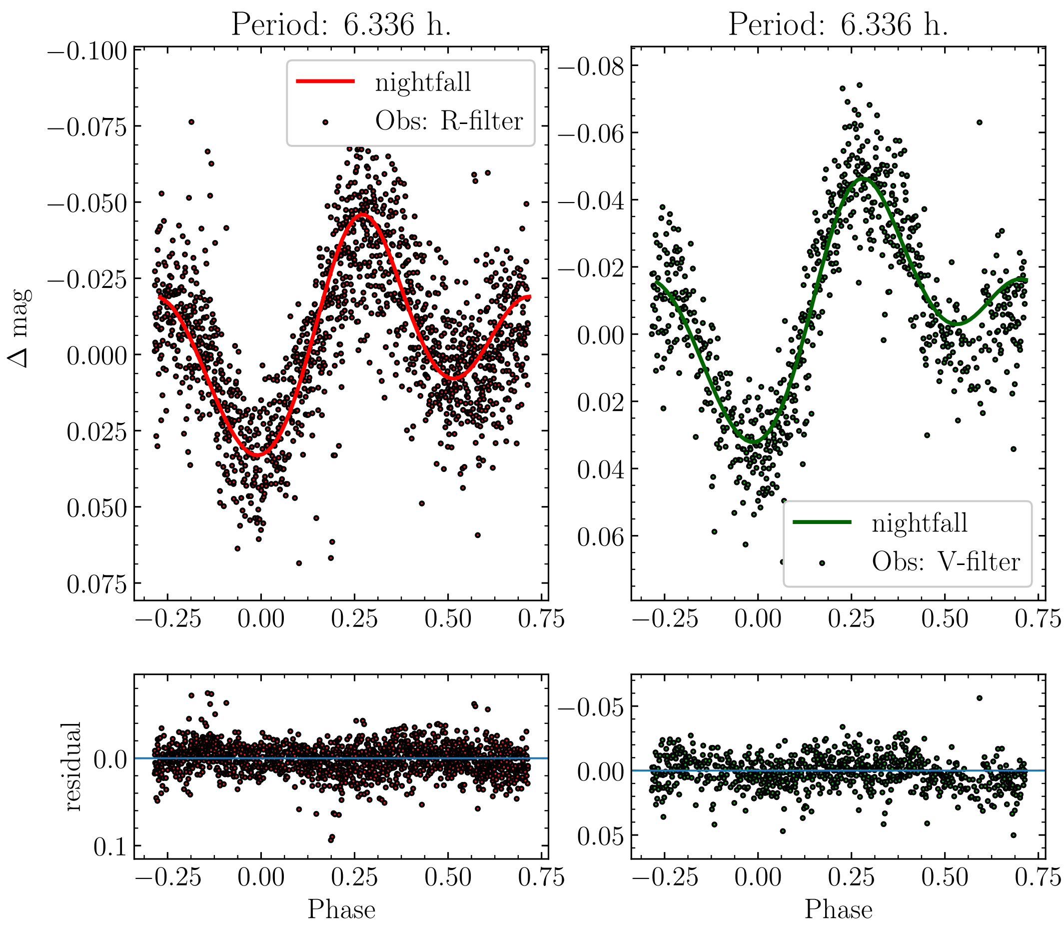


**Figure 10.** Top panels: folded observed light curves for filter $R$ (on the left) and filter $V$ and corresponding modeled light curves using "nightfall". Bottom panels: corresponding residuals.

*Acknowledgements:* The work was carried out within the framework of Project No. BR05236322 "Studies of physical processes in extragalactic and galactic objects and their subsystems", financed by the Ministry of Education and Science of the Republic of Kazakhstan.

This work has made use of data from the European Space Agency (ESA) mission *Gaia*

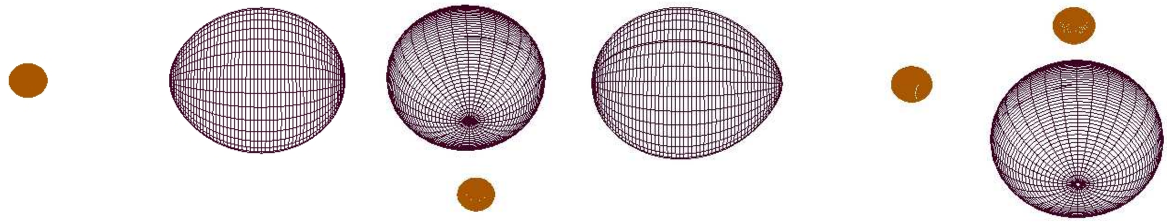

**Figure 11.** The space configuration of the binary system at phases = (0°, 90°, 180°, 270°) from left to right. This is elliptical variable system without the eclipse.

(`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.

The author thanks the anonymous referee for his/her thorough review of the manuscript and highly appreciates suggestions and comments, which significantly contributed to improving the quality of this paper.

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