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A Probable New BY Draconis Variable ZTF J021857.72+585950.1

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We present our analysis of new photometric and spectroscopic data for a poorly studied star with an uncertain variability type (BY Dra or EW), ZTF J021857.72+585950.1. The observations were carried out with the 0.6-m and 2.5-m telescopes of the Caucasian Mountain Observatory and the 1.25-m telescope of the Crimean Astronomical Station of the Sternberg Astronomical Institute (Lomonosov Moscow State University) in 2019–2024. We found a period of $0\overset{d}{.}279$ and demonstrated that brightness variations resulted from rotation of a spotted chromospherically active star of the BY Dra type, which is consistent with the AAVSO classification. Based on our low-resolution spectra, we classified the star as K1V and found profile variations of the Hα line both from night to night and during a single night. We also estimated the interstellar extinction $A_V = 0\overset{m}{.}27$ and distance to the star $d = 154$ pc.

1 Introduction

In recent years, solar-like stars receive considerable attention in the light of exoplanet detection. On the one hand, solar-like stars are promising hosts of planets in the habitable zone. But on the other hand, some of these stars are known to be variable, which complicates the planet detection. The stellar activity in the case of solar-like stars is believed to be due to the interplay of convection and magnetic fields that results in the appearance of dark spots on the stellar photosphere. The number and size of spots are not constant, and their evolution, together with axial rotation, creates not strictly periodic photometric variations with relatively low amplitudes and a wide range of time scales (see, e.g., Strassmeier 2009 and references therein). A number of large photometric surveys, such as OGLE, ASAS-SN, ZTF among others, have provided us with light curves for many solar-like stars, and based on these data, several statistical studies have been carried out (e.g., Chen et al. 2020), but only few stars were examined individually.

In this paper, we present our study of the star ZTF J021857.72+585950.1 that demonstrates similar patterns of variability. Miguel Muro Serrano was the first who announced the variability of the source to AAVSO VSX based on his observations carried out in December 2013. The star is included in the AAVSO database under the name GSC 03698-00538 with a period of $0\overset{d}{.}2788975$, initial epoch HJD 2456656.503, and phased light curve based on Muro's observations, NSVS and APASS data. The type of variability is given as BY[1]. In the ASAS-SN variable stars database, the star is named ASASSN-V J021857.78+585950.3 and classified as ROT (rotational variable), the period is not presented. The star is contained in the ZTF Catalog as an eclipsing binary with a period of $0\overset{d}{.}5579032$. The Simbad database also identifies the star as an eclipsing binary. Thus,

[1] https://www.aavso.org/vsx/index.php?view=detail.top&oid=359497

the type of variability is not well established so far. In our study, we attempt to clarify the mechanism of the star's variability and to determine its spectral type using our multi-band photometry and spectroscopic observations. Hereafter, we refer to the star as J0218+58.

2 Observations and reductions

We carried out $UBVR_CI_C$ photometry with the 0.6-m telescope (RC600) of the Caucasian Mountain Observatory (CMO) of Sternberg Astronomical Institute, M.V. Lomonosov Moscow State University (SAI MSU) in 2019–2024. The telescope is equipped with a set of Johnson–Cousins $UBVR_CI_C$ filters and an Andor iKon-L BV camera (2048 × 2048 pixels, the pixel size 13.5 μm; see Berdnikov et al. 2020 for details). Initially, we took one set of observations (2–3 frames in each band) per night, as our main goal was to monitor the post-AGB candidate IRAS 02143+5852 with a pulsation period of about $25^{\rm d}$ (Ikonnikova et al. 2024); the star under study in the present paper drew our attention as a variable object in the field: the scatter of magnitudes for the star was larger than for other stars of similar brightness. We were not able to deduce the type of the star's variability, but it was clear that the possible period was shorter than $1^{\rm d}$. Later, we started to observe the star more frequently, several times a night, which made it possible to derive its period and to make some conclusions about the type of variability. All the observational data were reduced in a standard way (debiasing, darking, and flat-fielding) using the MAXIM DL5 package. Then, aperture differential photometry was performed using a set of three comparison stars. The primary comparison star (st1) was selected in such a way as to minimize the photometric errors: the magnitude and color difference between J0218+58 and st1 appeared remarkably small. The other two stars were chosen to be a little brighter and fainter, at least in the V band. The constancy of the primary comparison star was monitored over the total time of our observations, as shown in Fig. 1. The estimated errors in differential magnitudes turned out to be $0\overset{\rm m}{.}009$, $0\overset{\rm m}{.}004$, $0\overset{\rm m}{.}004$, $0\overset{\rm m}{.}004$, $0\overset{\rm m}{.}005$ for the U, B, V, R_C, I_C bands, respectively. The general information on the comparison stars is presented in Table 1. We estimated the magnitudes of st1 using successive observations of photometric standards in the S23-246 and S23-436 fields of Landolt (2013). The adopted values are listed in Table 2.

Our VI_C follow-up photometry was performed with the 1.25-m telescope (ZTE) of the Crimean Astronomical Station (CAS) of SAI MSU during four nights in October, 2023. A set of Asahi filters was used together with an ASI6200MM Pro CMOS camera. The log of observations and mean errors are presented in Table 3. St1 was used as a primary comparison star. St2 and st3 were out of sight, since the FoV of the detector was $5\overset{\prime}{.}8 \times 3\overset{\prime}{.}9$. The data were reduced in a similar way as the RC600 data. The VI_C follow-up photometry was carried out as a part of test observations aiming to check the tracking accuracy of the 1.25-m telescope, so the weather conditions were different and sometimes not quite good: observational errors in the last column of Table 3 differ from night to night. Besides, there are gaps in light curves caused not only by worsening of atmospheric situation but also by technical reasons.

Our low-resolution spectroscopic observations of J0218+58 were carried out with the TDS spectrograph mounted on the 2.5-m CMO telescope (see Potanin et al. 2020 for the description of TDS and reduction procedures). The log of observations is presented in Table 4.

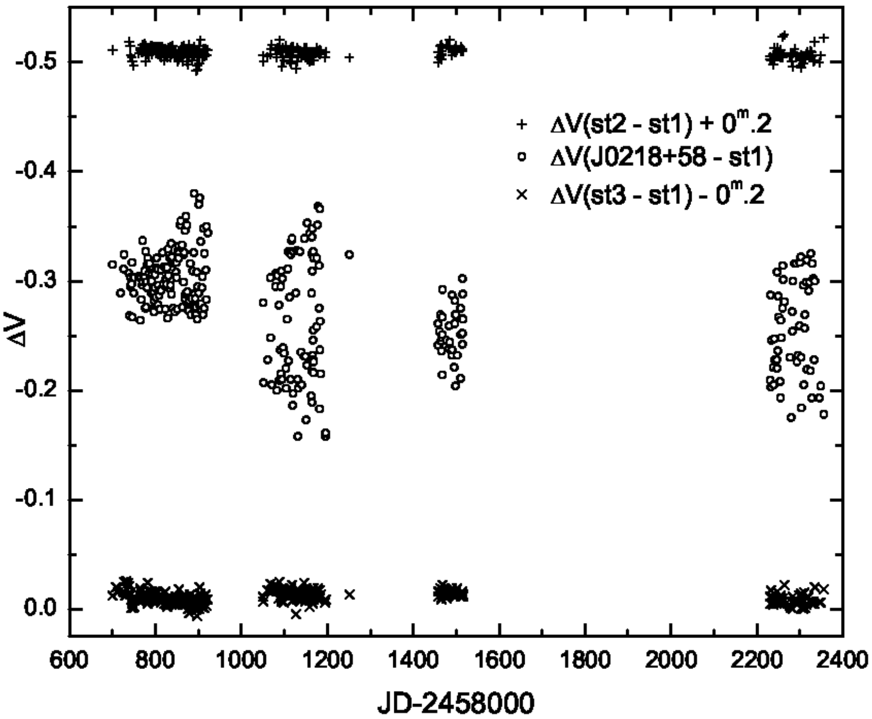

Figure 1. The differential light curve for J0218+58 and secondary comparison stars (st2 and st3) with respect to the primary one (st1). The points are nightly average values.

3 Seasonal light and color curves

In Figs. 2 and 3, we show the $UBVR_CI_C$ light and $B-V$, $V-R_C$ color curves based on the RC600 photometry. Each point represents an average of several estimates obtained during one set of observations. Such sets were usually performed once a night, but there were also nights with several sets separated by about an hour. These nights can be distinguished by concentrations of points in Fig. 2. It is clearly seen that the mean seasonal brightness of J0218+58 was not constant during the entire time interval of our observations. An especially drastic change occurred between March and July, 2020: the star faded by $0\overset{m}{.}03 - 0\overset{m}{.}05$ in all bands. Besides, the amplitude of light variations was also not constant: it was the smallest during the 2019–2020 season and the largest, in 2020–2021. It should be also mentioned that the maximum variation is the largest in the U band and gradually decreases to the I_C band. The peak-to-peak amplitude can change on a time scale of several months. The seasonal mean brightness and maximum variation in the $UBVR_CI_C$ bands are presented in Table 5. A mean brightness–amplitude correlation is seen: the star varies stronger (although the observed variation was never larger than $0\overset{m}{.}2 - 0\overset{m}{.}3$) when it is, on average, fainter and redder. The color variation is larger at longer wavelengths. The fact that the star tends to be redder when fainter, as can be seen from the color–magnitude diagrams presented in Fig. 4, implies temperature variations. On this point, we can suspect that the variability of J0218+58 is caused by axial rotation of a star with non-uniformly distributed and time-variable dark spots on its surface.

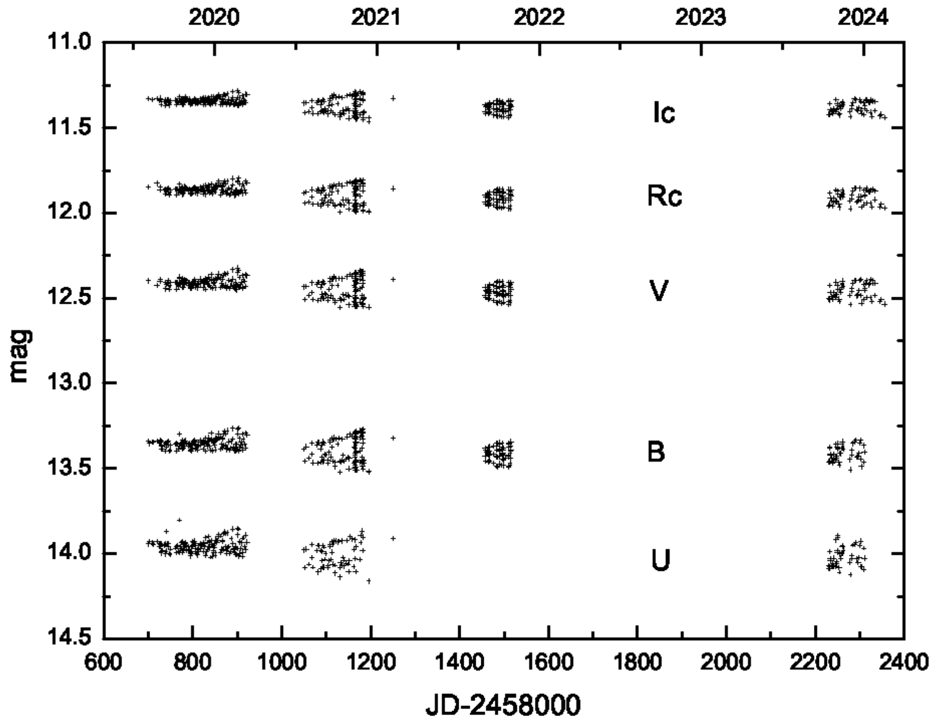

Figure 2. Complete $UBVR_CI_C$ light curves for J0218+58 based on the RC600 observations.

Table 1: Magnitudes of local standard stars

ID	Star	B	V	Reference
TYC 3698-296-1	st1	13.51	11.67	Høg et al. (2000)
UCAC4 746-021760	st2	12.64	11.99	Zacharias et al.(2013)
Gaia DR3 459181142673740416	st3	–	–	Gaia Collaboration (2022)

4 Search for periodicity

Aiming to derive the period for J0218+58 and having in mind that the amplitude (and likely phase) of light variation is variable, we constrained ourselves to two time-limited intervals: JD2459164–2459196 (32^{d} duration) and JD2459483–2459515 (32^{d} duration) that include sequences of nights when the star was observed more than once in the sense discussed in the previous section (several sets of 2–3 frames during one night). Then, using several statistical methods, namely, those of Lafler–Kinman, Barning, Renson, and the string method (our self-developed Python implementation of these methods is based on Terebizh 1992), a period of 0.279^{d} was found independently for each interval, and it was the same for the V and R_C bands. We failed to derive the period based on the whole

Table 2: Photometry for the primary comparison star (st1)

U	σ_U	B	σ_B	V	σ_V	R	σ_R	I	σ_I
14.245	0.009	13.649	0.010	12.713	0.006	12.198	0.004	11.715	0.010

Table 3: Log of the ZTE observations

HJD range	Band	Exposure, s	Number of frames	$\overline{\sigma}$
2460225.423– .516	V	60	130	0.0005
2460229.188– .381	V	30	494	0.001
2460230.214– .431	V	60	138	0.004
	I_C	60	137	0.006
2460232.187– .568	V	60	203	0.004
	I_C	90	203	0.005

Table 4: Log of spectroscopic observations

Date yyyy–mm–dd	Mean HJD	Exposure, s
2020–12–17	2459201.37	300×3
2022–03–14	2459653.29	600×3
2022–03–20	2459659.24	100, 600×3
2022–07–08	2459769.50	600×3
2022–08–01	2459793.51	600×3

Table 5: Mean magnitudes and maximum seasonal variation for J0218+58

Season	U	ΔU	B	ΔB	V	ΔV	R	ΔR	I	ΔI
(1) Aug 2019–Mar 2020	13.96	0.22	13.35	0.14	12.41	0.13	11.86	0.10	11.34	0.09
(2) Jul 2020–Feb 2021	14.01	0.29	13.39	0.25	12.45	0.22	11.90	0.19	11.37	0.18
(3) Aug 2021–Oct 2021	–	–	13.41	0.15	12.46	0.14	11.91	0.12	11.38	0.10
(4) Oct 2023–Feb 2024	14.02	0.22	13.41	0.17	12.46	0.15	11.91	0.12	11.38	0.11

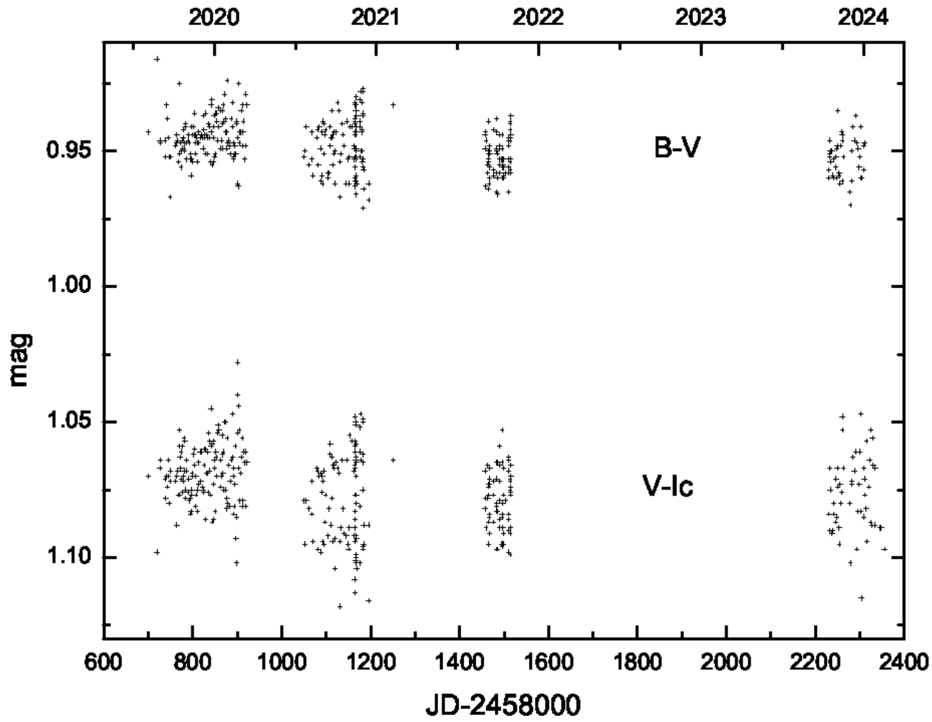

Figure 3. Complete $B-V$ and $V-R_C$ color curves for J0218+58 based on the RC600 observations.

set or seasonal intervals of observations, but, with the derived period, we were able to fold light variation in any not too long time interval. In Fig. 5, all the acquired RC600 V data are shown folded with this period. The red points correspond to the intervals used to determine the period for seasons (2) and (3) according to Table 5. The red points in season (1) correspond to the interval JD 2458870–2458922 that was not used in determining the period, they are highlighted just to illustrate the fact that the phase of minimum light is not constant, it can change on a time-scale of several tens of days or less. The pattern of light variation is also not constant: sometimes the rising branch is steeper, sometimes the falling one is steeper, and sometimes they are similar. The larger the amplitude, the longer time the pattern persists. The period did not vary, if it was at least detectable, during the entire time of our observations. Thus, we can state that the period is a rotational one and that variations of the light curve are probably due to evolution and migration of spots on the surface of a rotating star.

5 VI_C follow-up photometry

The V and I_C light curves (or their parts) are similar in shape, with the V peak-to-peak amplitude being a little larger (Fig. 6). On JD 2460229, there is a short $\sim 0^{\rm h}.5$ brightening by $\sim 0^{\rm m}.015$ in the descending branch of both light curves, which is not seen on JD 2460229 or JD 2460232, though the overall pattern of light variations remains the same during the time interval of observations. We consider this fact as an evidence for sporadic short-timescale flare-like variations of J0218+58. In Fig. 7, we present the VI_C phased light

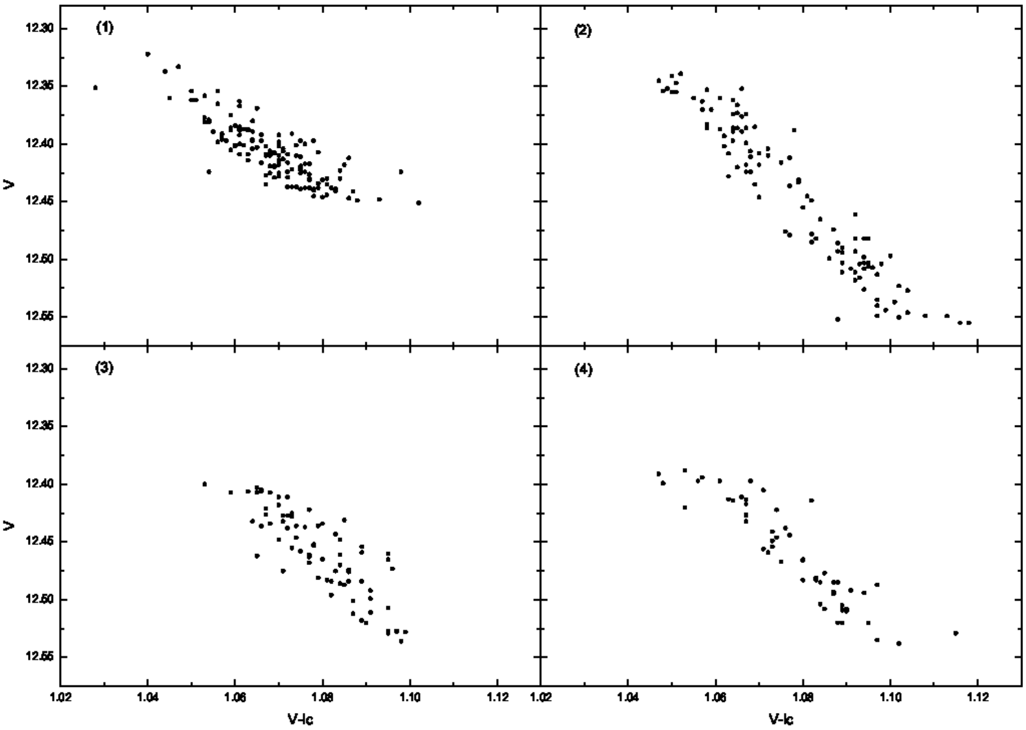

Figure 4. The color–magnitude diagrams based on RC600 observations for different seasons marked by numbers (1)–(4) according to Table 4.

curves folded with the period of $0^{\rm d}\!.279$ and then averaged over four observing nights with a step of 0.02 of the period to obtain the $V - I_C$ phased color curve that shows the object to be bluer when brighter. It is worth mentioning that the V phased light curve observed in October, 2023 looks like that obtained by Muro in December, 2013, with quite the same average magnitude but with the ascending and descending branches switched.

6 Spectra

Because of the low spectral resolution of our TDS spectra, we do not attempt to derive $T_{\rm eff}, \log g$, or [Fe/H] for J0218+58. Comparing our spectra to high-resolution spectra of Gaia benchmark stars (Strassmeier et al. 2018) downgraded to the spectral resolution of the TDS spectra, we can state that J0218+58 is an early K dwarf with more or less evident emission filling the hydrogen and CaII H and K lines. Spectral features used in temperature classification were selected following the recommendation of Gray and Corbally (2009) and are marked in Fig. 8, with the ratio CrI λ4254/FeI λ4250, λ4260 being the most reliable since it is insensitive to metallicity. It should be mentioned that ε Eri and 61 Cyg A whose spectra are shown in Fig. 8 are BY Draconis variables (Samus et al. 2017).

We did not find any significant variation in the emission in the CaII H and K lines: it never extended above the surrounding pseudo-continuum (Fig. 8). But we did detect a variation in the Hα profile. Not only the nightly average Hα profile differs from night

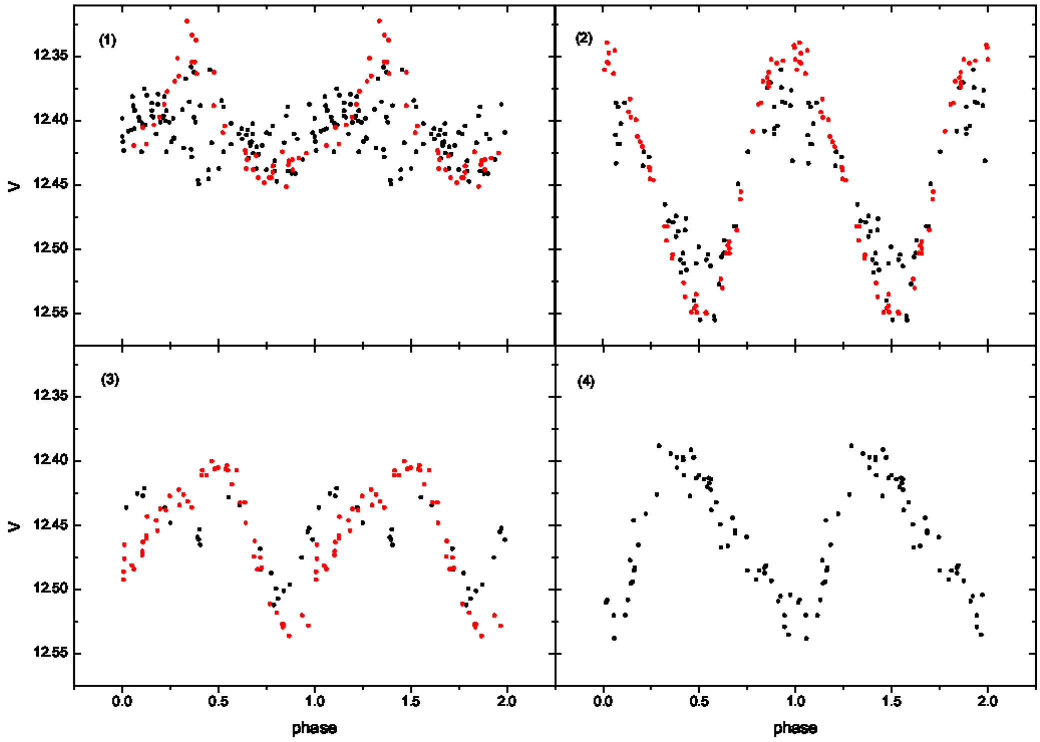

Figure 5. Phased V curves based on the RC-600 data folded with the period of $0\overset{d}{.}279$ for different seasons marked by their numbers (1)–(4) according to Table 5. Red points in panels (2) and (3) relate to the intervals used in determining period, red points in panel (1) were not used for this purpose, see text for details.

to night, but sometimes there are also changes within one night (Fig. 9). Unfortunately, the spectroscopic observations were not synchronized with the photometric ones, so we cannot specify the phase of photometric activity for the time when the spectra were taken, the phase being not constant.

7 Interstellar extinction and distance

If we take the mean brightness estimates for season (1) (Table 5) when the star was relatively bright and, therefore, mostly free of spots (if we consider J0218+58 a BY Dra-type star), and adopt the ZAMS color index and $E_{U-B}/E_{B-V} = 0.922$ for K1V stars from Straižys (1992), then the dereddened colors appear to be $(B - V)_0 = 0.86$ and $(U - B)_0 = 0.54$, which corresponds to a K1 main sequence star. The color excess is then $E_{B-V} = 0.08$, and the interstellar extinction is $A_V = 0.27$. Assuming the Straižys (1992) calibration of absolute magnitudes, we have $M_V = 6\overset{m}{.}2$ for a K1V star, and then the distance to J0218+58 is 154 pc.

According to the Gaia Data Release 3 (Gaia collaboration 2022; Gaia DR3), the distance to J0218+58 is 161.5 pc ($\pi = 6.15 \pm 0.01$ mas with RUWE=0.806), which is in excellent agreement with our estimate. Besides, Gaia DR3 provides the following parameters for the star: $T_{\rm eff} = 5300$ K, $\log g = 4.5$, [Fe/H]=–0.2, $R = 0.8R_\odot$, $L = 0.45L_\odot$,

$M = 0.9M_\odot$, and the age of 0.448 Gyr.

It is worth mentioning that Foster et al. (2000) considered the star a member of the open cluster Stock 2 with membership probability $\geq 50\,\%$ based on its proper motion. However, the adopted cluster distance of $\sim 300\,$pc is too large for J0218+58 to be a member.

8 Discussion

The emissions in the cores of the Hα, CaII H and K lines are indicative of chromospheric activity (Gray et al. 2003) caused by the stellar magnetic field that is believed to be closely linked to stellar rotation and to weaken with age. According to the study by Chen et al. (2020) based on the ZTF Data Release 2, the rotational periods of BY Dra variables range from 0.25 to 20 days. Thus, the rotational period of $0\overset{d}{.}279$ places J0218+58 among the youngest known BY Dra-type variables, where the spin-down effect has not yet occurred. However, it is worth mentioning that Chen et al. (2020) classified J0218+58 as a contact (EW type) eclipsing binary with $P = 0\overset{d}{.}5579$, a period twice longer than that derived in this study. We suppose that the wrong classification of J0218+58 by Chen et al. (2020) is the result of a combination of the non-constancy of amplitude and phase of J0218+58 with the low sampling (one observation per night) of the ZTF observing routine. Anyway, Fig. 5 demonstrates that the light curve of J0218+58 resembles those of eclipsing binaries only sometimes.

9 Conclusions

J0218+58 displays light variations with a range of amplitudes, varying in ΔV from $0\overset{m}{.}1$ to $0\overset{m}{.}22$, and a period of $0\overset{d}{.}279$ ($6\overset{h}{.}7$). To our knowledge, we are the first to classify J0218+58 as a K1V star and to detect profile variations of the Hα line both from night to night and during one night. We have estimated the interstellar extinction $A_V = 0.27$ and the distance to the star $d = 154\,$pc. The observed features of J0218+58 strongly favor the idea that it is a BY Dra-type variable and its variations are a result of rotation and nonuniform surface brightness due to dark spots. The classification of the star as an eclipsing binary given in the Simbad database should be revised.

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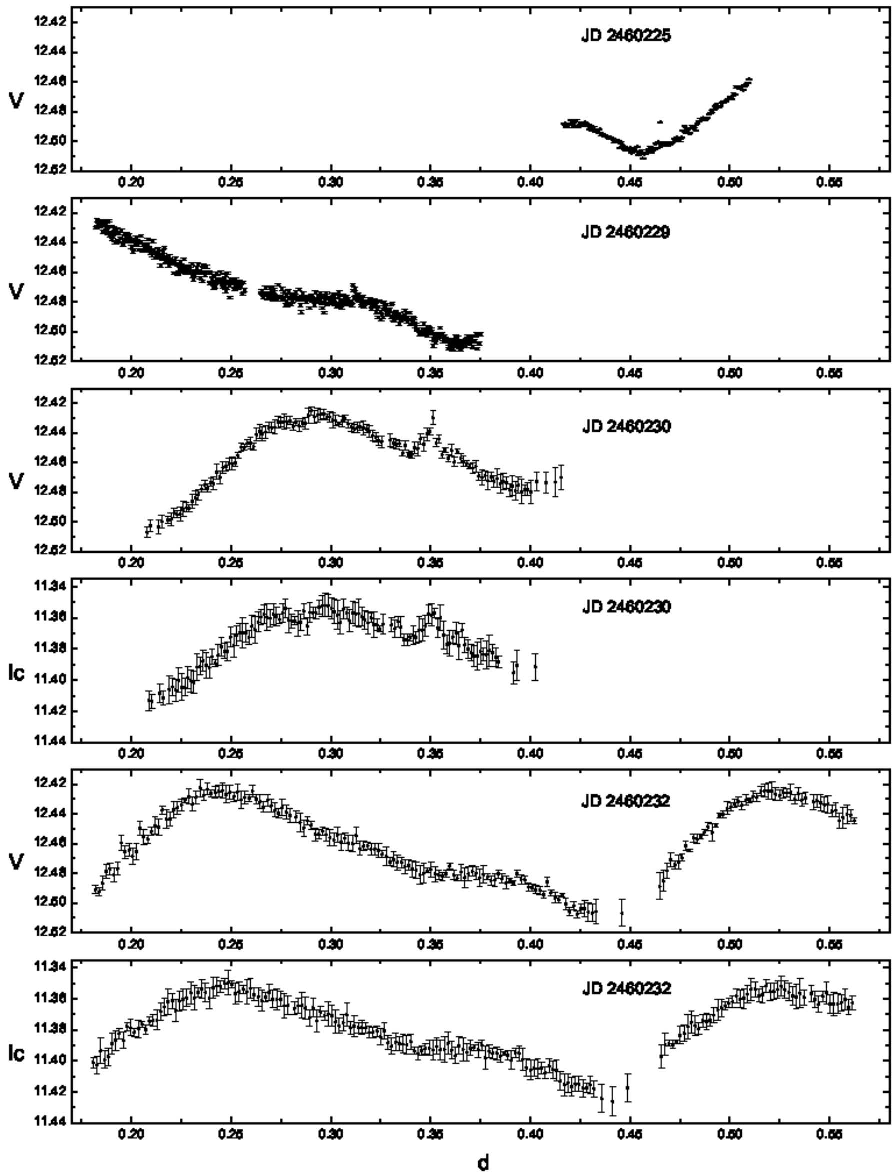

Figure 6. Individual VI_C light curves based on ZTE data.

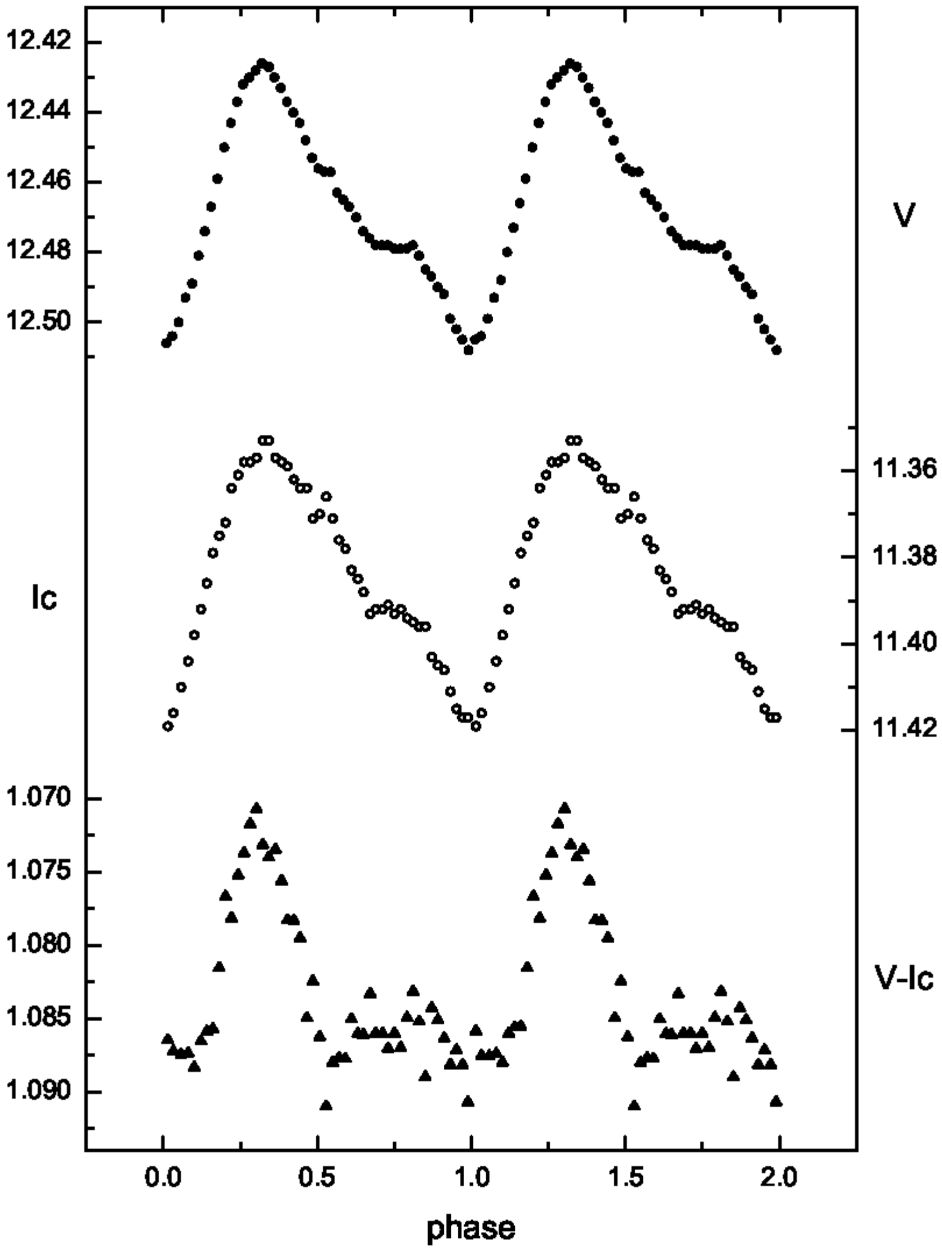

Figure 7. Mean VI_C and $V - I_C$ phased curves folded with the period of $0\overset{d}{.}279$.

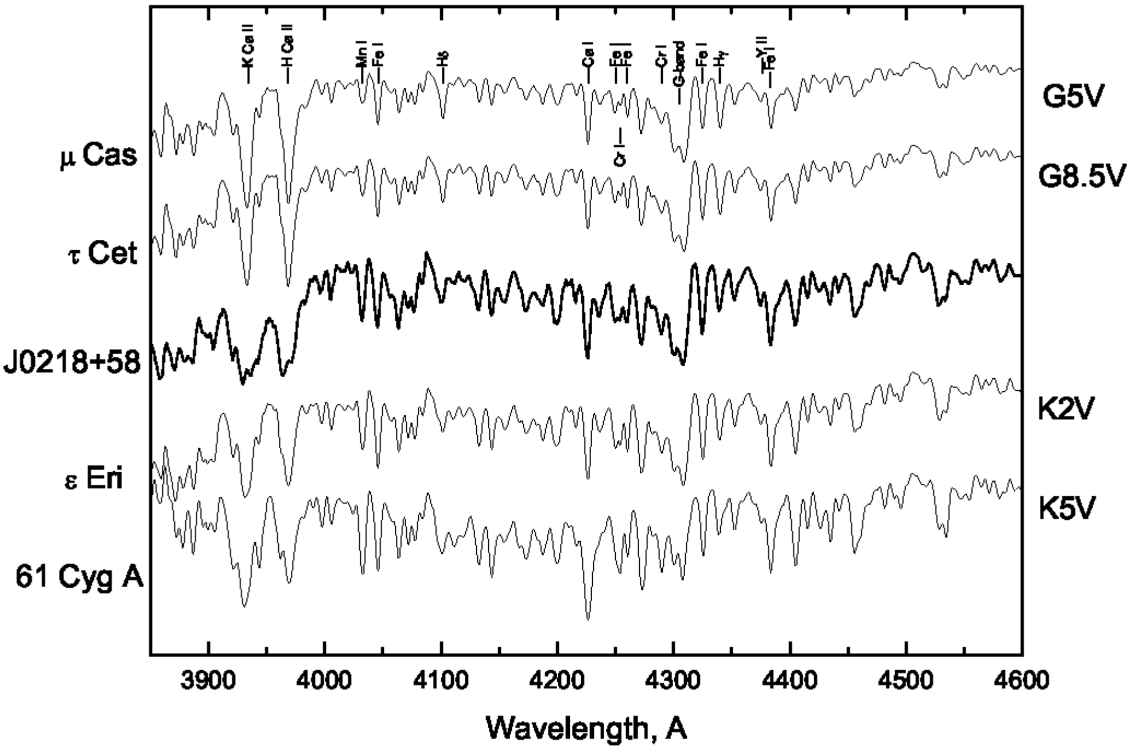

Figure 8. Normalized TDS spectrum of J0218+58 obtained on 2022-03-14 shown along with a temperature sequence for late G – early K dwarfs. The spectra were taken from Strassmeier et al. (2018) and vertically offset.

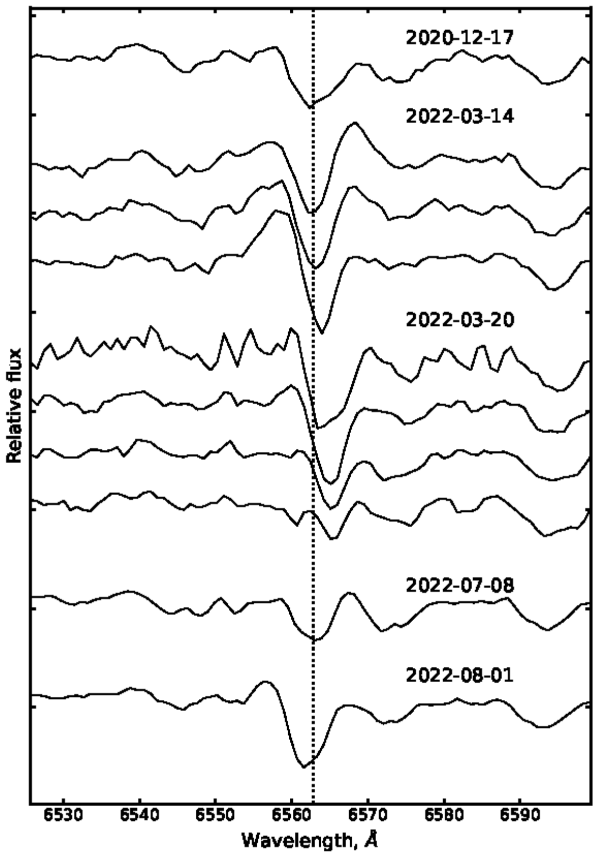

Figure 9. Variation of the Hα line. For the nights when no changes were detected, namely 2020-12-17, 2022-07-08, 2022-08-01, we give average profiles. For 2022-03-14 and 2022-03-20, we provide individual spectra obtained subsequently with 10 min intervals. The dotted line represents the rest-frame wavelength of Hα.