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USING CONSUMER-GRADE DSLR CAMERA AND SMALL TELESCOPE TO FIND NEW VARIABLE STARS

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ABSTRACT. Twenty-seven new variable stars were found in DSLR images captured from October 2017 to June 2019. All images were taken using unmodified Canon EOS 600D DSLR attached to a Skywatcher 150/750 Newtonian on a motorized equatorial mount. The variables were registered in The International Variable Star Index (VSX, AAVSO) as PMAK V1 .. PMAK V27 respectively. Most of them (twelve) were classified as semiregular variables of different subtypes, nine as eclipsing binaries (EA, EW, and EB), three rotating RS Canum Venaticorum-type stars, one rotating ellipsoidal variable (ELL), one Delta Scuti-type pulsating variable, and one as a possible nova-like (NL) star.

The setup and methodology used by the author allowed discovering of variables having a wide range of maximum brightness (from $8.^{m}9$ to $14.^{m}4$ in V band for stars described in the current work), variability range up to $\sim 0.^{m}1$ and less, and quite different periods of variability, from hours to hundreds of days. Although all those variables were detected using images taken by the author, detailed analysis and classification of stars required the involvement of additional data sources (automated sky surveys).

АБСТРАКТ. Двадцять сім нових змінних зір було знайдено на зображеннях, отриманих за допомогою цифрової дзеркальної камери за період з жовтня 2017 по червень 2019. Всі зображення були отримані за допомогою немодифікованої камери Canon EOS 600D, під'єднаної до телескопу-рефлектора Skywatcher 150/750. Телескоп був встановлений на моторизованому екваторіальному монтуванні. Знайдені змінні були зареєстровані у International Variable Star Index (VSX, AAVSO) як PMAK V1 .. PMAK V27, відповідно. Більшість з них (дванадцять) були класифіковані як напівправильні змінні різних підтипів, дев'ять як затемнювані подвійні (типів EA, EW та EB), три як зорі типу RS CVn, одна еліпсоїдальна подвійна типу ELL, одна малоамплітудна пульсуюча змінна типу DSCT та одна можлива новоподібна (NL) зоря.

Всі згадані зорі були виявлені на знімках, зроблених автором, для детального подальшого аналізу та класифікації були залучені додаткові джерела даних (автоматизовані огляди неба).

Використана автором система з цифрової дзеркальної камери та невеликого телескопу має чутливість, яка дозволяє ефективно виявляти змінні з широким діапазоном яскравостей у максимумі (від 8.9 до 14.4 зоряної величини у фільтрі V для зірок, що описані у даній роботі) та діапазоном змін до ~0.1 зоряної величини та навіть меншим у випадку яскравих зір (з зоряною величиною біля 11 .. 12 у фільтрі V або меншою).

Серед змінних зір, які були знайдені протягом даного дослідження, кілька яскравіші за 10 зоряну величину у максимумі. Це може свідчити, що існує багато невідомих яскравих змінних, які не охоплені автоматичними оглядами (такі яскраві змінні можуть становити проблему для автоматичних оглядів, які націлені на більш тьмяні об'єкти).

Довгі серії зображень, отриманих за період, більший за рік, дозволяють виявляти змінні з широким діапазоном характерної тривалості змін, від годин до сотень днів.

Keywords: variable stars, aperture photometry, DSLR.

1. Introduction

Aperture photometry with a Digital Single Lens Reflex (DSLR) camera is a popular method among amateur astronomers for the estimation of stellar brightness (Hoot, 2007; Kloppenborg et al., 2012; Pieri, 2012; Zhang et al., 2015; Blackford et al, 2016). Despite that consumer-grade DSLR cameras use Bayer matrix with non-photometric color filters, after proper calibration they can be used for the precise aperture photometry (Kloppenborg et al., 2012; Pieri, 2012; Blackford et al, 2016). In the current work, the author demonstrates that the accuracy of photometry with a modest DSLR camera and a small 150mm Newtonian makes us possible to discover new variable stars having a relatively small range of variability (from several tenths of magnitude to $<0\overset{m}{.}1$) in a light-polluted suburban area.

Although most of the variables listed in catalogs (see, for example, probably the most comprehensive catalog of known variables: The International Variable Star Index (VSX) (Watson et al., 2006)) are discovered by automated sky surveys (such as ASAS-SN (Kochanek et al., 2017), SuperWASP (Butters et al., 2010), NSVS (Woźniak et al., 2004), ZTF (Masci et al., 2019), etc.), in many cases the stars, discovered by individual astronomers (both professional and amateur) or small groups of them are better described and properly classified. Results of a search for the new variables in sequences of DSLR images are presented in the current work.

2. Data acquisition and processing

A setup used by the author consists of 150mm f/5 Newtonian on tracking equatorial mount. Canon EOS 600D DSLR was attached to the telescope instead of an eyepiece to get images at the prime focus. The field of view of the setup was $1.7^{o}\times1.1^{o}$. All observations have been carried out in a suburban area of Kyiv (Ukraine). Image acquisition was carried out following the procedure described by Blackford et al. (2016). Calibration frames (bias-, dark- and flat- frames) were taken at the end of each observing session with the same ISO level, the same exposure was used for dark frames as for the science images. Exposure of 30 seconds was used in most cases.

Raw images from the camera were transformed into FITS format, then were calibrated with master bias, dark and flat frames. As far as the camera uses a three-color Bayer matrix, channel separation was used to produce sets of images in green, blue and red filters in FITS format. To increase the signal-to-noise ratio (SNR), several individual images (usually 5) were averaged (stacked) to produce an image with better SNR, this also diminishes the effect of atmospheric scintillations. Before averaging, the star alignment procedure was applied to individual images. Measures for final light curves were made on those stacked images, however, for the initial search, all images taken during an observing session (night) were aligned and stacked together. So the initial search for new variables was done on a set of such nightly-averaged images.

Transforming from camera raw images to FITS, preparation of master bias, dark and flat frames, channel separation, and image stacking were done using a set of utilities created by the author (Pyatnytskyy, 2018); calibration of science images and star alignments before stacking were done using IRIS software (Buil, 2010). The search for the variables was done with MuniWin/C-MuniPack software (Hroch, 2014).

A series of images (green channel only) correspond to different observing nights (one averaged image for each night) was analyzed by the "Find Variables" module of MuniWin package. To make a search more efficient, cropped parts of the full field of view were used. MuniWin makes aperture photometry for all stars in the analyzed field of view for the series of images producing "Standard Deviation of the Magnitude vs. Magnitude" plot. "Outlying" points in that plot may correspond to variable stars.

Each "suspected" star (having a big standard deviation of magnitude across the sequence) was checked for existence in the VSX and catalogs covered by the VizieR Catalogue Service (VizieR). If the variable turned out to be a new one, aperture photometry for the suspected star was done on short stacks (5×30s), a light curve was built and a period (if exists) was estimated. For long periodic and semiregular variables the measures were averaged by sessions (nights), for short-period stars individual measures were used. The aperture photometry was done with AstroImageJ software (Collins et al., 2017), an ensemble approach (several comparison stars) was used.

As far as DSLR uses Bayer matrix with non-standard filters, data had to be transformed (as far as it is possible) into a standard photometric system (this is especially important in case of ensemble photometry because color indices of the stars in the ensemble are different). Magnitudes of the target star measured relative to each comparison star in the ensemble were transformed from ones obtained for Bayer matrix filters to values corresponding to the Johnson V filter using a synthetic V-filter methodology (VSF) (Pieri, 2012). In this methodology a "corrected" sygnal of camera's green filter is used:

$$G_c = G + aR - bB \tag{1}$$

where G_c is the corrected signal of the green filter, R, B are signals of the red and blue filters, respectively. Coefficients a and b were selected to minimize the difference between Jonhson V filter output V_j and corrected signal of the green channel using the ensemble of stars with known brightness:

$$V_j = k(G_j + aR_j - bB_j) \tag{2}$$

Here k is a scaling factor. Author of VSF methodology states that it generally gives better precision for red stars than the standard transformation technique (Pieri, 2012).

Calibration of the author's setup (finding transformation coefficients) was done using M67 standard field provided by the AAVSO (American Association of Variable Stars Observers). To make a solution of the system of equations (2) more robust, the author used a simplified approach proposed by Pieri (2019) in which a assumed to be equal to b.

The resulting magnitude for each light curve point was an average of those transformed values obtained relative to all comparison stars in the ensemble.

For better estimation of the period and other star's characteristics data from ASAS-SN (Kochanek et al., 2017), SuperWASP (Butters et al., 2010), and APASS (Henden et al., 2018) surveys were used together with data obtained by the author for further analysis. In some cases, when the author's data had poor quality (for faint stars or stars at the margin of a field of view where star's image was severely distorted by optical aberrations) only data from the mentioned surveys were used. In such cases, original images were used to detect a fact of variability itself only.

A period search for periodic and semiregular variables was performed with VStar software. If a star was proven to be a new (previously unregistered) variable, it was sent for registration to the VSX.

2. Results

Using data collected from October 2017 to June 2019, 27 new variables have been found in five starfields. They were registered in the VSX as PMAK V1 .. PMAK V27 respectively. The characteristics of the variables are summarised in Table 1. Most of the new variables (16) were found in a single field in Cygnus around an object 2MASS J21313973+3529220 (this is a known variable indexed as Romanov V4 in the VSX) which was the main observation target in this field. There were more than 60 observation nights for this field from October 2017 to December 2018. Such a relatively long series of images allowed us to discover periodic and semiregular variables having a wide period range, from hours to hundreds of days.

All of the new-found variables have relatively small variability range (less tnan one magnitude), three of them have a range less than $0.^{m}1$ in V band (see Table 1). This proves the good sensitivity of the setup and accuracy of the method. It is interesting to note that several of the stars are brighter than 10^{m} in maximum which makes them problematic targets for some automatic surveys (for example, ASAS-SN nominal saturation limit is between 10^{th} and 11^{th} magnitude in V-band (Kochanek et al., 2017)). It may indicate that there are many bright unknown variables to search for.

Additionally, photometry in Johnson V and Johnson B bands were measured for some of the new variables (as noted before, only V-band data calculated using VSF approach were used for period analysis). For two-band photometry, standard transformation (see Blackford et al., 2016; Kloppenborg et al., 2012; Henden & Kaitchuck, 1982) from Bayer green and blue channel was used based on transformation coefficients obtained from observations of M67 standard field provided by the AAVSO. Examples of light curves are shown in Fig. 1. It is seen that the author's data (PMAK) for V band are in a good agreement with ASAS-SN V band which confirms the reliability of measurements.

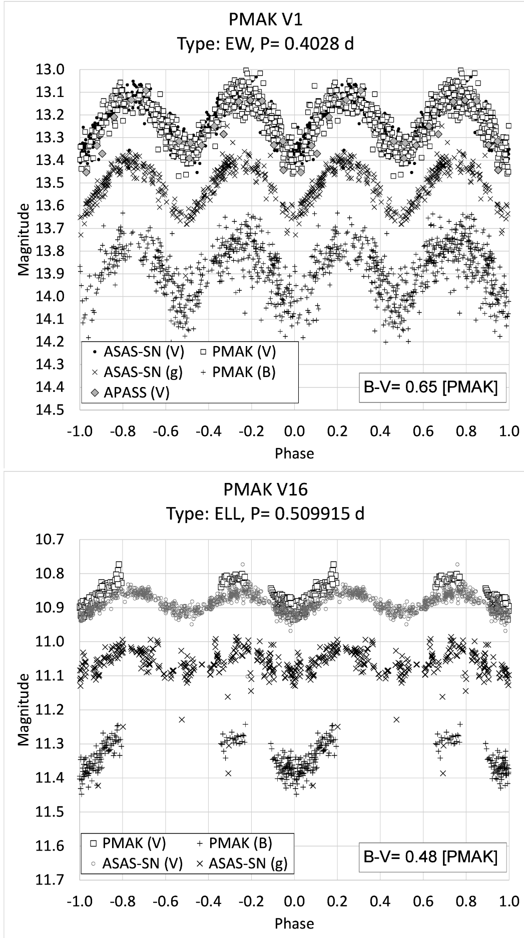

Fig. 1: Upper pane: Folded light curves of PMAK V1. Epoch (2458119.913 HJD) differs from those specified in the VSX by half of the period. Lower pane: Folded light curves of PMAK V16: a variable with the smallest range ($0.^{m}07$ in V band) for which light curves with author's data are available. The period has been refined.

3. Conclusion

Setup of a small (150mm f/5 in the current case) telescope equipped with DSLR camera has sufficient sensitivity which allows one to effectively detect new variables having brightness up to $\sim 14^{m}$ in V band and variability range up to $\sim 0.^{m}1$ or even less for bright stars (of about 11^{m} .. 12^{m} and brighter).

Among the stars found during the current research, several are brighter than 10^{m} in maximum. This is evidence that there exist many unknown bright variables which are worth searching for.

Long series of frames taken over a period of more than a year allows ones to detect variables with a wide range of characteristic duration of changes, from hours to hundreds of days.

Table 1: New variables found in DSLR images collected from October 2017 to June 2019 (data from the VSX)

VSX name	Catalog designation	Coordinates J2000	Type	Period (d)	Epoch (HJD)	Range (V)	D[2]
PMAK V1	2MASS J21303361+3531290	21:30:33.62+35:31:29.0	EW	0.40280	2458119.712	13.10 - 13.38	
PMAK V2	2MASS J21300019+3537282	21:30:00.18+35:37:28.2	SRB	44.9	2458124	13.5 - 14.0	
PMAK V3	2MASS J21300722+3559550	21:30:07.23+35:59:55.1	SRS	26.3	2458159	12.8 - 13.4	
PMAK V4	2MASS J21321559+3507213	21:32:15.59+35:07:21.3	SRB	43.5	2457741	12.6 - 13.1	
PMAK V5	TYC 2712-1327-1	21:30:17.88+35:10:25.4	EA	4.7392	2458119.23	13.15 - 13.6:	10
PMAK V6	2MASS J21282963+3511375	21:28:29.63+35:11:37.5	RS	44.69	2457187.75	11.96 - 12.25	
PMAK V7	TYC 2712-183-1	21:28:43.22+35:33:39.0	SRB	49.3	2458161	10.9 - 11.4	
PMAK V8	TYC 3196-2125-1	21:41:45.58+44:05:49.4	SR	126.9	2458176	11.26 - 11.63	
PMAK V9	BD+34 4421	21:27:51.02+35:34:20.9	SRD	36.4	2455827	8.9 - 9.3	
PMAK V10	2MASS J21335644+3518525	21:33:56.44+35:18:52.5	RS	13.214	2458234	14.4 - 14.9	
PMAK V11	2MASS J21345319+3542016	21:34:53.19+35:42:01.4	EW	0.4011496	2457139.898	14.10 - 14.65	
PMAK V12	2MASS J21314096+3542209	21:31:40.97+35:42:20.9	SRB	30.27	2457755	14.1 - 14.6	
PMAK V13	2MASS J21283912+3502390	21:28:39.12+35:02:39.1	EW	0.556504	2457554.65	13.16 - 13.34	
PMAK V14[1]	2MASS J21341089+3520285	21:34:10.89+35:20:28.5	EA	1.095355	2457139.792	14.3 - 14.9:	18
PMAK V15	BD+63 173	01:20:20.51+64:01:30.3	SRB	33.4	2457725	9.7 - 10.15	
PMAK V16	TYC 4034-1138-1	01:24 21.07+63:16:02.7	ELL	0.50991	2457204.34	10.86 - 10.93	
PMAK V17	2MASS J21400903+4410037	21:40:09:04+44:10:03.8	SRS	27.6	2457749	12.84 - 13.17	
PMAK V18	2MASS J21430699+4302568	21:43:07.00+43:02:56.8	EA	3.50965	2457729.45	12.67 - 12.9	8
PMAK V19	2MASS J13353214+7317138	13:35:32.15+73:17:13.7	RS	12.86	2457278	13.11 - 13.52	
PMAK V20	2MASS J21444177+4356214	21:44:41.79+43:56:21.4	SRS	24	2457740	12.76 - 13.12	
PMAK V21	2MASS J20335348+5956506	20:33:53.49+59:56:50.7	DSCT	0.143553	2457266.455	12.62 - 12.65	
PMAK V22	2MASS J21315159+3549238	21:31:51.59+35:49:23.8	EA	14.492	2457216.5	13.12 - 13.27	9
PMAK V23[1]	2MASS J01153742+6328048	01:15:37.41+63:28:04.8	EB	0.693731	2457777.855	14.28 - 15.08	
PMAK V24	BD+34 4443	21:31:06.42+35:24:19.6	SRS	19.57	2455840.5	9.68 - 9.88	
PMAK V25	TYC 2712-846-1	21:34:11.36+34:56:04.1	SRD	279	2457745	11.63 - 11.76	
PMAK V26	TYC 3583-1129-1	20:56:16.68+50:15:52.2	EA	3.94548	2457105.65	11.94 - 12.03	7
PMAK V27	2MASS J13275559+7324530	13:27:55.60+73:24:52.9	NL:	–	–	12.81 - 13.05	

[1] Co-discoverers: B. Sesar et al., 2017
[2] Primary eclipse duration for EA-type binaries as a fraction of the width of one complete eclipse cycle in %

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