Open Access Online Journal on Astronomy and Astrophysics
Acta Astrophysica Taurica
www.astrophysicataurica.org

Acta Astrophys. Tau. 3(2), 39–45 (2022)

Investigation of flare activity of the red dwarf star EV Lac based on original observations and using the data from ground-based and space surveys

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Submitted on March 26, 2021

ABSTRACT

The problem of energetics of flare activity of dwarf stars in the lower main sequence of the Hertzsprung-Russell diagram is relevant in the context of the detection of powerful flares (superflares) and the possibility of assessing such phenomena on the Sun in the past and future. A brief historical review of the EV Lac original researches is presented, and the modern databases containing information on photometric observations of the star are described. The main attention is paid to the observations of EV Lac made by the TESS observatory.

Results of the analysis of flare activity of the star according to the data of the TESS project are presented. The most typical flares have been demonstrated. The dependence of flare activity of EV Lac on the phase of its axial rotation has been studied. The dependence of the number of flares on the phase and energy is illustrated. The segment of the phase of the EV Lac light curve, which contains flares with the highest energies, is indicated.

Key words: UV Cet variable star – EV Lac, flare activity, phase dependence, flare energy

1 Introduction

The eruptive variable star EV Lac (BD+43 4305) is the red dwarf of the spectral type $M4.0V$; its mean magnitude $V = 10^{\rm m}$. Apparently, the first publication in which EV Lac is indicated as a flare star in the list of objects was released in 1952 (Lippincott, 1952). Although no flares have been recorded for the star in this study, but it attracts increasing attention of observers.

The object is one of the brightest representatives of UV Cet-type flare stars. It is conveniently located in the sky at a declination of about 44 degrees; therefore, considerable time is spent for this star at the Crimean Astrophysical Observatory (CrAO). The bulk of information is devoted to EV Lac in the paper “Flare red dwarfs and stellar activity of the solar type – a half-century of studies at the Crimean Astrophysical Observatory” (Gershberg, 2017) and in the monograph “Physics of mid- and low-mass stars with solar-type activity” (Gershberg et al., 2020).

The studies of EV Lac have been carried out at CrAO since the early 1960s of the past century (Chugainov, 1965). The statistics of flare activity of the star was published in Gershberg and Chugainov (1969). The paper on the photoelectric observations of flare stars was published in the same year in which the photometry of EV Lac flares was described in four spectrum bands: U, H_α, G, and V (Chugainov, 1969). The paper of Chugainov (1972) is devoted to the spectrocolorimetric observations of flares of the star carried out at CrAO. In the same year, Shakhovskoy, Efimov (1972) reported on the polarization of the EV Lac flare observed at CrAO.

High time-resolved observations of the star in the optical range at a frequency of 240 MHz were conducted at CrAO simultaneously with the 76 m radio telescope of the Jodrell Bank Observatory (Great Britain) in 1961–1964 (Lovell, Chugainov, 1964).

In collaboration with researchers from SAO and MAO a technique for high-speed photometry and colorimetry of flare stars as well as for EV Lac observations was elaborated at CrAO (Shvartsman et al., 1988; Zhilyaev et al., 2007).

The paper of Alekseev, Kozhevnikova (2017) is devoted to a search for cyclic activity of EV Lac. It was suggested on a possible cyclicity with a characteristic time of about 30 years.

During 1967—1975, the observers from CrAO took part in the international cooperative programs on observations of flare stars, including EV Lac (Gershberg, Shakhovskaya, 1983).

Similar projects were continued in the 1980s and 1990s (Berdyugin et al., 1995; Alekseev et al., 1994, 2001).

According to the data from observational campaigns, nine strong flares with amplitudes $\Delta U = 1^{\rm m}.8$ were detected (Alekseev, Gershberg, 1997b).

The parameters of the chromosphere in the quiescent and excited states were first estimated at CrAO. A phenomenon of the mass ejection type was detected based on the splitting of the ionized helium line during a strong flare (Abranin et al., 1998).

The first observations with the aim of searching for a correlation between EV Lac flares in the optical and gamma-ray spectrum ranges were apparently carried out at CrAO (Alekseev et al., 1995). The possibility of studying flare activity in the optical and decametric spectrum ranges was also explored (Abranin et al., 1994). The optical flare of EV Lac with a total duration of 2.4 seconds was recorded with high confidence at the ASTRON space station on February 24, 1984 (Gershberg, Petrov, 1986).

Particular attention at CrAO was paid to the modeling of the EV Lac emission spectrum (Alekseev et al., 2003) as well as to the analysis of the coverage of its photosphere by spots in the framework of the suggested model of stellar spottedness (Alekseev, Gershberg, 1997a).

2 Ground-based survey observations of EV Lac

The transition from the traditional monitoring of stars to studying their behavior using modern databases is caused by the extensive observational data appeared in recent decades as a result of conducting different survey programs. However, the basic problem of observations with short-focus objectives in the wide-field sky surveys is a low resolving power of instruments. Taking into account that at a distance of about 25 arcsec from EV Lac there is the AG+44 2118 object (V = $12^{\mathrm{m}}.00$, spectral type G, the binary or multiple system), then the objects may be photometrically unresolved. Thus, the EV Lac brightness can increase due to the unresolved component AG+44 2118 by more than $0^{\mathrm{m}}.2$. No data for EV Lac are available in the surveys of SDSS DR12[1], CTRS DR2[2], KELT[3], HATNet[4], and OGLE[5].

2.1 AAVSO

The AAVSO[6] database (The American Associations of Variable Stars Observers) contains information on 1894 observations of EV Lac between January 1, 1973 (UTC 23:45:01) and December 31, 2019 (UTC 01:00:00). Among them 1806 observations are visual; 51 were obtained in the V-band (CCD); 7 were taken in the B-band (CCD); 30 were obtained with a CCD without a filter; 16 visual observations were acquired when the object was faint.

Visual observations available in AAVSO (Fig. 1) have a low accuracy but, taking into account a significant length of the series, can serve as an addition to studying trends in long-term variability of EV Lac on intervals of several decades.

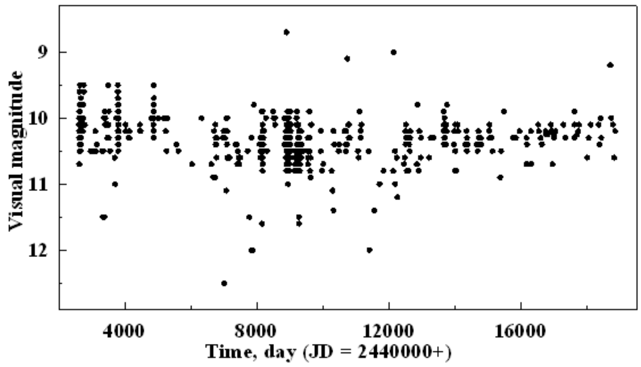

Fig. 1. Visual observations of EV Lac from AAVSO.

2.2 SuperWASP

The system of cameras SuperWASP[7] composed of 200 mm telescopic lens with a resolution of 13.7 arcsec per pixel performs a survey of the whole sky (northern and southern hemispheres) for 40 minutes. In the brightness variation range of EV Lac SuperWASP provides an accuracy of photometry of better than 1 % (Pollacco et al., 2006). In the SuperWASP database there are 3 objects within a radius of 15″ denoted in the 1SWASP catalog as J224649.73+442002.3, J224650.28+442015.2, and J224651.49+441955.1. The light curves of each of these objects, including EV Lac, consist of ~6000 measurements, which were taken with three cameras. They have a lot in common; their brightness varies within 0.2–2 mag.

Taking into account that the deviation in brightness is directed to both greater and fewer magnitudes, it is impossible to interpret these variations as flare activity or an abrupt brightness drop. Since the brightness variation amplitude associated with axial rotation amounts to about 0.03 mag (Subsection 3.5), then the further using of the SuperWASP data requires a more detailed analysis.

2.3 ASAS-SN

The ASAS-SN[8] project involves 24 observatories mounted all around the world. These are systems of 14 telescopes having an aperture of 14 cm and recording objects in the range from 9 to 18 mag in the V-band with a resolution of ~8 arcsec per pixel (Kochanek et al., 2017).

The resolution of ASAS-SN enables the data on EV Lac and AG+44 2118 to be divided. EV Lac was observed from HJD 2457007.73718 to 2458434.83892. Totally, 264 observations were conducted in the V-band. The star shows a brightness decrease from 10.75 to 11.32 mag without manifesting significant flare activity. AG+44 2118 changes its brightness from 11.95 to 12.01 mag and can serve as a reference star for EV Lac while elucidating peculiarities of its brightness variations in the observed period.

[1] https://www.sdss.org/dr12/
[2] http://nesssi.cacr.caltech.edu/DataRelease/
[3] https://keltsurvey.org/
[4] https://hatnet.org/
[5] http://ogle.astrouw.edu.pl/
[6] https://app.aavso.org/
[7] https://wasp.cerit-sc.cz/
[8] http://www.astronomy.ohio-state.edu/asassn/index.shtml

2.4 KWS

The automated system involves a combination of short-focus objectives of 50 mm (between 2010 and 2012) and 105 mm (from 2012 to present day), both are with a relative aperture of $F/2.0$. The field of view of telescopes is greater than $5.0° \times 7.5°$. The exposures are 30 and 15 seconds in the first and second variants, respectively. A photometric accuracy of 5 % or less is achieved for objects with a magnitude in the V-band from 5^m to 11^m (Maehara, 2014).

EV Lac and AG+44 2118 are represented in the KWS[9] database independently, despite a low resolution of the optical system. For EV Lac, the catalog contains 806 measurements in the V-band obtained between August 14, 2011 and November 14, 2020; 792 measurements in the Ic-band from July 11, 2013 to November 14, 2020; two records in the B-band on September 10, 2015. AG+44 2118 was observed in the V-band from August 14, 2011 to November 9, 2020; the file storages 170 measurements.

EV Lac has not shown significant brightness variations in both the V- and Ic-bands for about 10 years. Insignificant fluctuations within 0.2 mag in the V band with a period close to 3 years in the framework of additional studies may be interpreted as cyclic brightness variations. No similar brightness fluctuations are observed for AG+44 2118.

At the conclusion of considering EV Lac observations based on the data of ground-based surveys one should note that a small series of brightness estimates of the object (N = 68) was performed within the NSVS project (Wozniak et al., 2004). The star shows no significant brightness variations in the R-band ($9^m.02$–$9^m.16$) for more than 130 days from MJD 51353.284926 to 51486.127633.

3 EV Lac observations from space observatories

The long-term surveys in the optical spectrum range for the objects of the whole sky had not been performed until the launch of HIPPARCOS[10]. The similar situation had been until the launch of the ROSAT [11] X-ray observatory. In the late XX and early XXI centuries, a series of orbital observatories was launched, including those of not the optical range (mainly gamma-ray and X-ray) but equipped with optical telescopes to search for the candidates for identifying with newly discovered sources and transit phenomena. The databases of some of them contain information on EV Lac.

3.1 HIPPARCOS

For 37 months of observations after the launch in 1989, HIPPARCOS has cataloged more than 2.5 million objects included into the Tycho-2 catalog (Hog et al., 2000). The time series of observations have been acquired for more than a million objects (ESA, 1997).

EV Lac observations were carried out between December 27, 1989 and February 19, 1993 for over three years (1154 days). Totally, 248 brightness estimates were obtained in the H-band in the range of $9^m.89$–$12^m.20$. Note that the bulk of magnitude estimates are in the range of 10^m–$10^m.5$, and only 7 estimates are fainter. Meanwhile, at least three impulse events of increased brightness with an amplitude ranging from 0.2 to 0.3 mag from the mean value in a series were observed.

3.2 ROSAT

The X-ray observatory carried out observations between June 1, 1990 and February 12, 1999. Following the results of the ROSAT mission, a series of catalogs was compiled; the most comprehensive of them was published in 2016 (Boller et al., 2016). Concerning EV Lac, this catalog contains information on two observational runs, one of which represents a pronounced flare (Fig. 2). Observations were carried out on July 11, 1990 at UT = 13:19:52.0 and on December 21, 1990 at UT = 11:54:45.0.

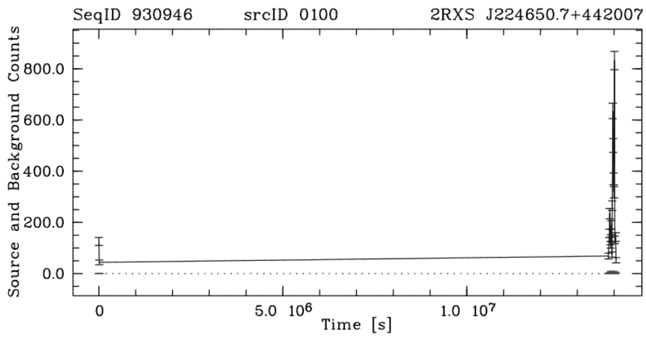

Fig. 2. The EV Lac X-ray flare recorded with the ROSAT observatory. The background level is shown with the dotted line.

3.3 ASCA

The ASCA[12] observatory was put into orbit on February 20, 1993 and finished its observations on July 14, 2000. The most comprehensive catalog of ASCA observations contains information on 1343 sources observed between May 1993 and December 1996 (Ueda et al., 2001). In 2000, it was reported on the extreme X-ray flare with energy of $7 \cdot 10^{34}$ erg observed on EV Lac between July 13, 1998 at UT = 06:10 and July 15, 1998 at UT = 01:40 (Favata et al., 2000).

3.4 OMC INTEGRAL

The Optical Monitoring Camera[13] (OMC) onboard the INTEGRAL mission is intended for optical observations of the main objectives explored by instruments of the gamma-ray and X-ray ranges. It has a 50 mm aperture and covers a field of $5° \times 5°$. OMC is capable of detecting optical sources brighter than $V \sim 18^m$ from the previously compiled input catalog (Domingo et al., 2003). The camera makes records of sources with brightness from 7^m to 17^m with an accuracy up to 0.1 mag.

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9 http://kws.cetus-net.org/~maehara/VSdata.py
10 https://www.cosmos.esa.int/web/hipparcos
11 https://www.mpe.mpg.de/ROSAT
12 https://heasarc.gsfc.nasa.gov/docs/asca/
13 https://sci.esa.int/web/integral/-/30626-the-optical-monitoring-camera-omc

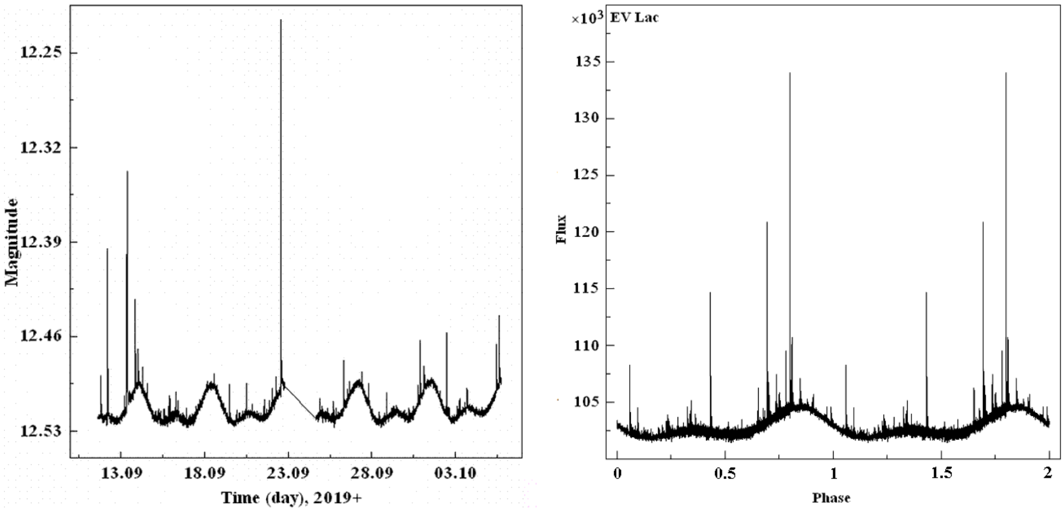

Fig. 3. The EV Lac light curve constructed from the TESS data (left panel). The convolution of the observed series with a period of $4^d.378$ (right panel).

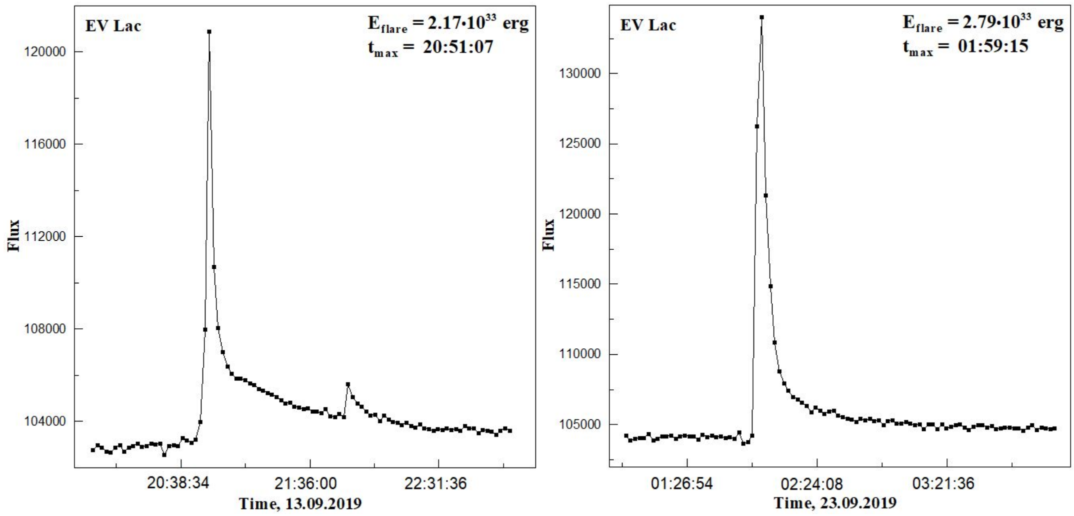

Fig. 4. Fragments of the EV Lac light curve with the detected flares. The figure shows the maximum time of the flare and its energy.

OMC observed EV Lac during two runs: on November 20, 2006 at UT = 16:57:27 and on July 25, 2020 at UT = 12:54:19. Twenty-one measurements were totally performed. During the first run the object's brightness varied from $10^m.19$ to $10^m.23$, and during the second run – from $10^m.50$ to $10^m.61$. Meanwhile, it was noted that the object was badly approximated by the PSF function, and the center of the star's image differed from the object's coordinates. It is obvious that in this case, taking into account that OMC is a short-focus camera, the AG+44 2118 star fell into the field of measurement.

3.5 TESS

To date, TESS[14] is the most productive orbital observatory that performs a survey of the whole sky with a temporal resolution of 20 seconds and 2 minutes and a length of the series in one observational run of about 20 days.

TESS (Ricker et al., 2015) is equipped with four wide-field refractors with objectives having the 1 cm apertures and fields of view of 24° × 24°. The CCD matrix of 16.8 megapixels serves as a detector for each telescope. Radiation is recorded in the 600–1000 nm spectral range. The TESS input catalog (Stassun et al., 2019) contains information on 1727987580 objects.

Suggesting the observations within the TESS survey to be the most qualitative and precise, we have selected EV Lac observations from the database of this space observatory. To elucidate the statistical and dynamical peculiarities of the manifestation of EV Lac flare activity, the observational series of this star were analyzed. The observations were carried out during 24 days within the period from September 12 to October 6, 2019. The TESS light curve of EV Lac is shown in Fig. 3. To analyze the statistics of flare activity depending on

[14] https://www.nasa.gov/tess-transiting-exoplanet-survey-satellite

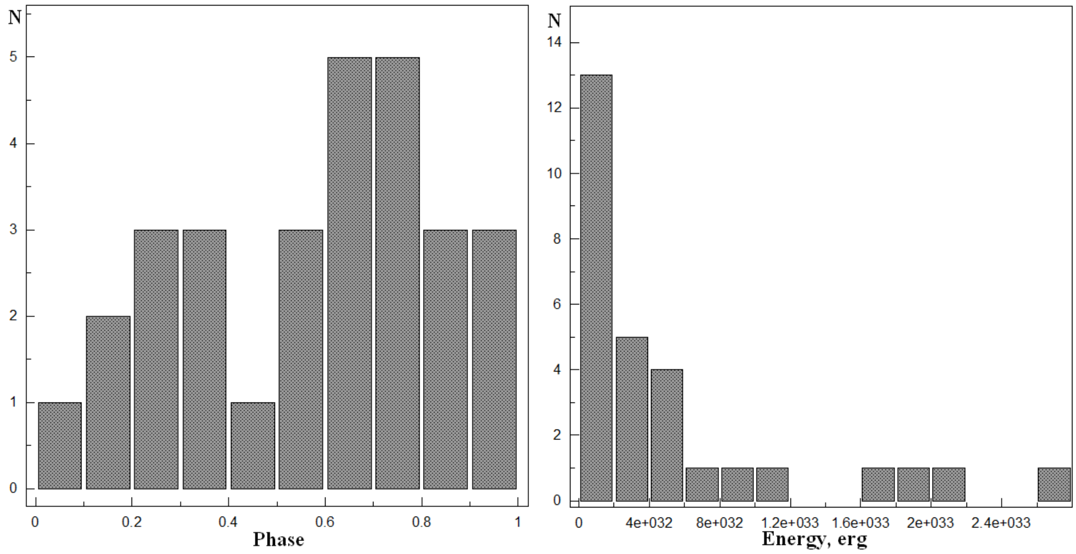

Fig. 5. Histogram of the distribution of the number of flares depending on the phase (left panel). Histogram of the distribution of flares depending on the energy (right panel).

the known period of stellar rotation $4^d.378$ (Pettersen, 1980), the convolution of the observed series with the mentioned period was performed (Gorbachev, Shlyapnikov, 2020).

Table 1 from the above mentioned paper lists values of the calculated energy for some flares identified from the light curve. The flare energies were calculated according to the technique described in Shibayama et al. (2013). The most characteristic flares by the profile for red dwarfs are illustrated in Fig. 4. Figures 5 and 6 demonstrating statistical studies of the flare activity of EV Lac are taken from Gorbachev, Shlyapnikov (2020). As can be seen from the image (Fig. 5, left panel), the maximum of the distribution falls on phases of 0.6–0.8, which corresponds to the increasing in brightness of the object. One can also note that the energy of most flares do not exceed $2 \cdot 10^{32}$ erg (Fig. 5, right panel). The distribution of flare energies depending on the phase is represented in Fig. 6 which shows that the flares with the greatest energies fall on the region of 0.7–0.9 of a phase. The analysis of the TESS light curve of EV Lac during 24 days made it possible to ascertain 29 significant flares of stellar activity, for which the energy was calculated and a more larger number of flares with a small amplitude. The greatest frequency of flares is observed in the region of 0.6–0.8 of a phase curve, whereas a number of flares with the greatest energies are at 0.7–0.9, i.e., delayed by 0.1 of a phase. The interest in using the TESS data for studying the flare activity of EV Lac as well as that of other flare stars (Gorbachev, Shlyapnikov, 2021) increases with accumulating the results of observations. Thus, the paper of Muheki et al. (2020) is devoted to the analysis of flares and their relation with coronal mass ejections and, as well as a given paper, provides information on the analysis of flare activity of EV Lac from TESS observations.

The authors analyzed 27 flares and calculated their energy. But the absence of the table with results did not make it possible to conduct a comparative analysis of our calculations with those published in Muheki et al. (2020). The main objective in the cited paper was a comparison of the high-

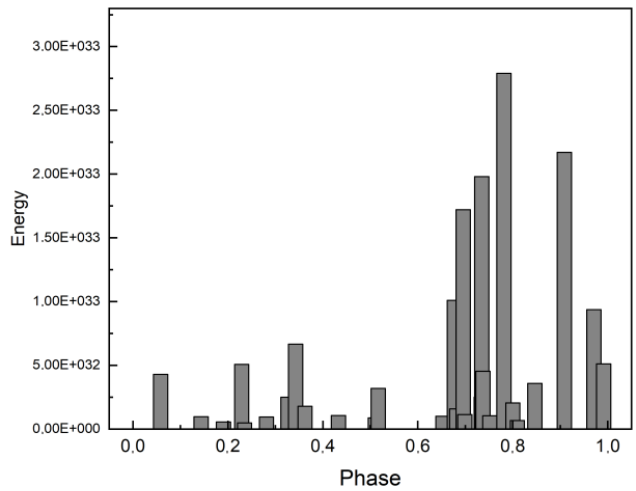

Fig. 6. Distribution of the energy of EV Lac flares depending on the phase according to the TESS data

resolution spectral observations of EV Lac and an analysis of the ratio of continuum fluxes in the spectral band of TESS to the energies emitted in the H_α, H_β, and He II 4686 Å lines. None of the flares showed a conspicuous coronal mass ejection.

4 Conclusions

As a result of the conducted work, we have made a brief historical review of the basic studies of EV Lac which were carried out at the Crimean Astrophysical Observatory and in collaboration with colleagues from other institutions. Taking into account a fast data accumulation within the ground-based and space survey projects, the most productive of them are considered, particularly those containing information on the observations of EV Lac. Particular attention is paid to the data on the star obtained with the TESS orbital station. Based on the results of processing these observations the energies of the detected flares have been calculated, and a statistical analysis of the flare activity of EV Lac has been conducted depending on the rotation phase caused by the presence of magnetoactive formations.

Acknowledgements. This investigation has made use of the NASA Astrophysical Information System and the instrument to access the VizieR catalog, as well as the SIMBAD database, operated at CDS, Strasbourg, France. The initial description of the VizieR and SIMBAD services was published in Ochsenbein et al. (2000); Wenger et al. (2000). The authors are grateful for the possibility to access the data on EV Lac from the international database AAVSO provided by the observers from around the world, which we used in this study. We have also made use of the information from the first dataset WASP DR1 (Butters et al., 2010) provided by the WASP consortium, and the computing and storage facilities at the CERIT Scientific Cloud, reg. no. CZ.1.05/3.2.00/08.0144, which is operated by Masaryk University, Czech Republic. This paper is partially supported by the Russian Foundation for Basic Research, project № 19-02-00191. The authors are deeply indebted to R.E. Gershberg and M.M. Katsova for useful remarks which helped to improve the paper.

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