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Solar-type Activities and Brightness Variations in Three Binary Star Systems

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Abstract

This survey presents our study of brightness variations exhibited by three binary star systems at various time-scales.

We use observational data obtained from the Transiting Exoplanet Survey Satellite (TESS); the 2m telescope of the National Astronomical Observatory (NAO) Rozhen and the American Association of Variable Star Observers (AAVSO) International Database. Observations cover the different periods of time in optical bands of the selected binary systems: the visual binary with a solar-type dwarf 61 Cyg (Cygnus); the spectroscopic binary YY Gem (Gemini) and the ER UMa type dwarf novae IX Dra (Draconis). The indicated types of variability in brightness are compared to some solar type of activities, including flares, seen in the optical and X-ray bands. States of outbursts are also detected during the observational periods and we explore the possibility that the studied stars could exhibit solar-type bursts. We examine the similarities in the manifestation properties between the three targets and the Sun, and discuss their feasible sources.

Keywords: Solar activity; Flares; Binary stars: K and M dwarfs.

1. Introduction

Solar activity is known to manifests in different types of phenomena as flares, coronal mass ejections, bursts, prominences, solar wind, eruptions, sun spots.

The most energetic phenomena on the Sun are Solar flares [Shibata & Magara, 2011]. Solar flares are powerful bursts of electromagnetic radiation produced from the Sun. They could last from minutes to hours, within the wavelengths' range from radio waves to gamma rays [Hathaway, 2015].

These types of activity are found in various types of stars. In binary stars a repeated variability in the brightness, known as flares, is a common occurrence [Pearson et al., 2005]. The flares appear particularly in systems with accretion discs in time scales of hours to days, with amplitudes in a range of 1 ÷ 3 magnitudes. Flaring is known to be an ordinary phenomenon among K and M dwarfs [Hartman et al., 2011].

Two typical members of these spectral classes are 61 Cyg and YY Gem.

The first object 61 Cyg is a visual binary that contains a solar-type dwarf of spectral type K5 - 61 Cyg A and a K7 dwarf 61 Cyg B [Boro Saikia et al., 2016]. The distance to the star is only 3.5 pc. 61 Cyg A has a radius of 0.665 ± 0.005 $R_\odot$ and mass $M_A \sim 0.66\ M_\odot$ [Kervella et al., 2008; Takeda et al., 2007]. Its effective temperature is measured as $T_{eff}=4545 \pm 40$K and the mass transfer value is $\approx 0.06 \times 10^{-12}\ M_\odot\ yr^{-1}$.

The rotation periods are: 35 ± 1.7 days for the primary A and 38 ± 1.5 days for the secondary B [Donahue et al., 1996]. The object is defined with its solar-type variability, and 61 Cyg A is also known as a strong X-ray source.

The activity cycle of 61 Cyg A is about 7.3 ± 0.1 years [Baliunas et al., 1995, Robrade et al., 2012]. In its maximum active state, the X-ray luminosity of 61 Cyg A reaches $L_X = 6 \times 10^{27}$ erg s^{-1} with released energy about 1×10^{31} erg in soft X-rays. This corresponds to activity level of $\log L_X/L_{bol} = (-5.9) - (-5.4)$.

For the K7 component 61 Cyg B only a chromospheric activity cycle of ~ 11.7 ± 0.4 yr is obtained [Hempelmann et al., 2006]. The registered flare of the B component is even with higher luminosity $L_X = 1.4 \times 10^{28}$ erg s^{-1} and releases 7×10^{31} erg. The activity level is measured as $\log L_X/L_{bol} = (-5.6)$.

Observations report that flares produced by active M-dwarfs stars are more energetic and more frequent than those of the Sun [Kajikiya, 2025].

The second object YY Gem (Gemini) is a spectroscopic eclipsing binary system. It consists of two M-dwarf components of dM1e spectral type with almost equal parameters, considered as: the masses are $M_1 = M_2 = 0.57 \pm 0.005\ M_\odot$; radii of the components: $R_1 = R_2 = 0.61 \pm 0.005\ R_\odot$, and the separation of the two components: $a = 3.83\ R_\odot$ [Brancewicz & Dworak, 1980; Torres & Ribas, 2002]. The mean value of the effective temperature is 3820±100 K [Torres & Ribas 2002]. The orbital period of the system is determined as Porb ~ 0.814 days [van Gent, 1931].

Flare activity of YY Gem was observed photometrically [Doyle et al., 1990], spectroscopically in UV [Saar & Bookbinder, 2003] and X-ray [Stelzer et al., 2002], and also using radio data [Jackson et al., 1989].

YY Gem is one of the M-stars which flaring activity in UV and X-ray are more powerful than those on the Sun [Haisch et al., 1990].

The X-ray luminosity in the soft band during the observed flares was estimated to be in a range: $(2-8) \times 10^{29} - 10^{33}$ erg s^{-1} [Tsikoudi & Kellett, 2000].

The optical light curves of the flare give the flux values in the maximum of $\approx 7.4 \times 10^{30}$ erg s^{-1} in U and $\approx 5.9 \times 10^{30}\ erg\ s^{-1}$ in B, with the total energy in optical bands 5×10^{33} erg [Butler, 2015].

For comparison, in average registered solar X-class flare emits roughly 1×10^{27} erg s^{-1} in the 0.2−5.0 keV band [Robrade et al., 2012].

The third object is of different type, IX Dra (Draconis) is a binary system, a dwarf nova of ER UMa-type. The orbital period of IX Dra is estimated as Porb ~ 0.066 days [Kato et al., 2017].

IX Dra manifests superoutbursts with a supercycle length of 53 days and outbursts amplitude of 2.5 mag [Ishioka et al., 2001]. Photometrically obtained magnitude range of the objects is 14.7 - 18.2 in V band [Otulakowska-Hypka et al., 2013].

Superhumps during the supercycle length were also detected with a period of 0.067 days. They are known as periodic variations in brightness, which periodicity is a few percent longer than the orbital period. Then the mass ratio of the two binary components is obtained, using the average superhump period Porb=0.0672 days and q=0.101 [Liu, 2023].

In this paper, we present observational results both from Transiting Exoplanet Survey Satellite (TESS) and the 2 m telescope of the National Astronomical Observatory (NAO) Rozhen for 61 Cyg A, YY Gem and IX Dra (Section 3). A comparison of the solar-type activities between the three stars and with those of the Sun is given in Section 4.

2. Observational data and results for the three binary star systems

In this section, we apply data from TESS (The Transiting Exoplanet Survey Satellite) observations of the northern sky. The TESS is designed mainly to search for and observe the transiting Earth-sized exo-planets [Günther et al., 2020]. Its field of view is divided into 26 sectors, which gives the opportunity to observe more than 200 000 selected objects, including bright stars. The light curves of the objects are analyzing with a 2- minute cadence [Ricker et al., 2015].

Here we present observational data taken from sectors 75, 72 and 15, for the three binary stars: 61 Cyg, YY Gem, IX Dra. The time intervals of the obtained data are different for the three objects, as follows: for 61 Cyg it is January 29 - February 26, 2024 (59796.602 -

59823.767 MJD); for YY Gem it is November 11 - December 6, 2023 (60259.684 - 60285.086 MJD); for IX Dra we have: August 15 - November 2, 2019 (58710.863 - 58736.909 MJD). Where MJD in the squares means the corresponded Modified Julian Date.

The details for the TESS observations and data are seen in Table 1 below.

Table 1. *TESS observational details for the three binary stars.*

TESS data details / Object	**61 Cyg A**	**YY Gem**	**IX Dra**
Exposure Time [sec]	20	120	120
Observation Time [MJD]:	59796.602 - 59823.767	60259.684 - 60285.086	58710.863 - 58736.909
Sector Number:	75	72	15
Period, defined at zeropoint t0:	24.693	14.91	9.491
Period derivative:	0.15	0.15	0.0002
Wrapping phase:	0.5	0.5	0.5
Algorithm/Method:	Lomb-Scargle	Lomb-Scargle	Lomb-Scargle
Number of bins N:	400	300	300

The resulting light curves and power-period diagrams were created from the Simple Aperture Photometry (SAP) Flux data. They show the activity in these objects during the observational time-intervals (see Figures 1, 2, 3). The light curves were constructed as Flux-rate [e-/s] (electrons per second) vs. time in [days]. The appearance of flares is detected in two of the objects 61 Cyg A and YY Gem, seen both at the flux vs. time curve and in the frequency analysis diagrams. The maximum amplitudes of these light variations are $3.5 \pm 0.0003 \times 10^9\ e/s$ for 61 Cyg A and $0.21 \pm 0.0002 \times 10^9\ e/s$ for YY Gem.

The observed variations in the flux-rate of IX Dra are less powerful and with a lower amplitude 8.31 ± 0.0005 x 10 e/s. They could be identified as regular outbursts that prolong for 2 -- 5 days, which is in agreement with the object dwarf nova nature and its registered so far bursts activity [Ishioka et al., 2001].

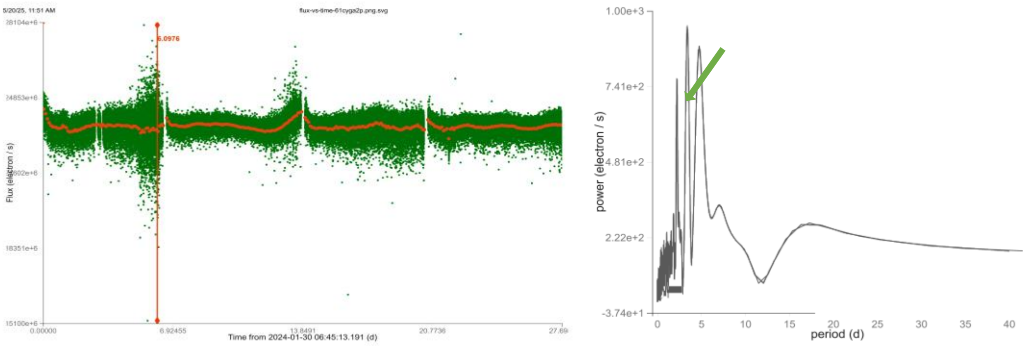

Figure 1. *Light curve of 61Cyg A, created with data obtained from TESS for the observational time interval (January 29 - February 26, 2024) (left panel). Two flares are indicated during this period. The more intensive one is marked with a red vertical line. The dotted red line denotes the binned curve with number of bins 400 for the optimal fit. (Right panel): Frequency analysis, power-period diagram of 61Cyg A with the TESS data for the same observational time. The stronger flare is marked with a green arrow.*

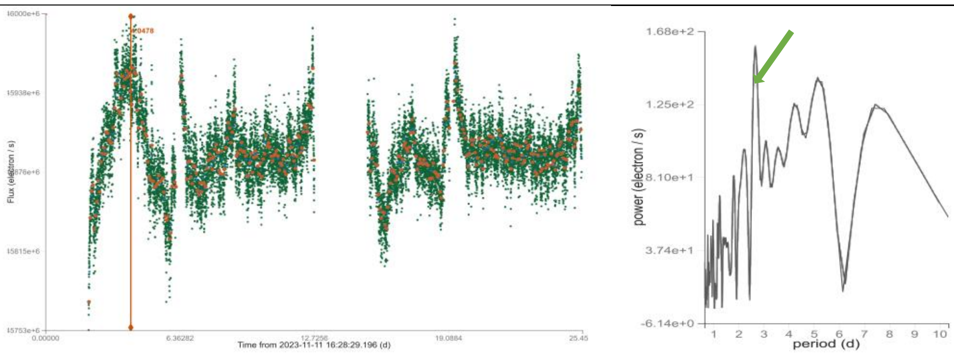

Figure 2. *Light curve of YY Gem, created with data obtained from TESS for the observational time (November 11 - December 6, 2023) (left panel). Two flares are indicated during this period. The more intensive one is marked with a red vertical line. The dotted red line denotes the binned curve with number of bins 300 for the optimal fit. (Right panel): Frequency analysis, power-period diagram of YY Gem, obtained with the TESS data for the same observational time. The flare is marked with a green arrow.*

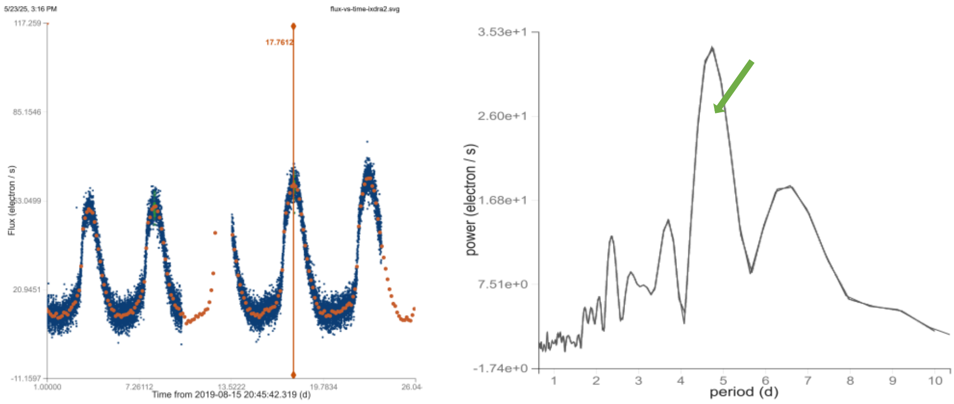

Figure 3. *Light curve of IX Dra, created with data obtained from TESS - observational time (August 15 - November 2, 2019) (left panel). Several outbursts are indicated during this period. The more intensive one is marked with a red vertical line. The dotted red line denotes the binned curve with number of bins 300 for the optimal fit. (Right panel): Frequency analysis, power-period diagram of IX Dra, obtained with TESS data for the same observational time-interval. The green arrow marks the outburst.*

For the third object IX Dra, we perform photometric observations with the 2 m telescope of the National Astronomical Observatory (NAO) Rozhen. The two-channel focal reductor FoReRo2 and two identical CCD cameras Andor iKON-L were used to obtain the observational data. Data reduction was performed with standard tools and aperture photometry. On the night of October 15 2023, the maximum brightness of the star was 16.5 ± 0.02 magnitude in V band and 18.2 ± 0.04 mag in B. The estimated amplitude of variations in V was 0.71 mag and 0.85 mag in the B band. During this time, according to the AAVSO data the object was in a cycle of an outburst's state, with a maximum magnitude of 15.87 ± 0.021 in V. Then, the observed from us curve's shape is most likely an orbital hump that appear during the outburst period (see Figure 4).

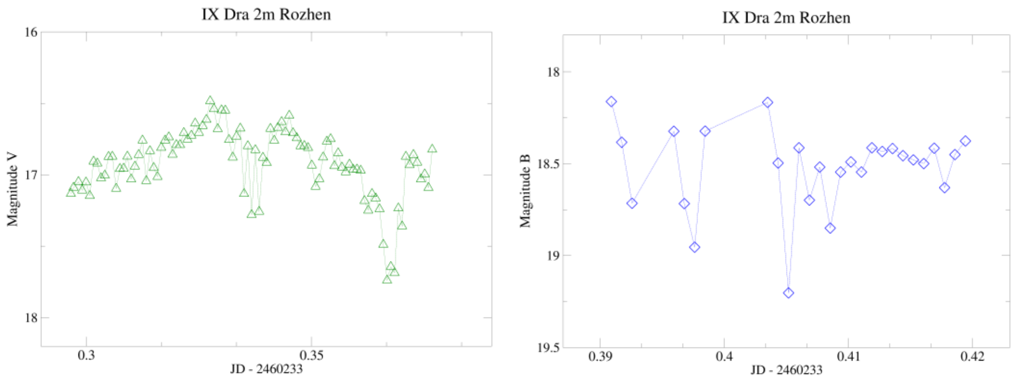

Figure 4. *Light curves obtained by photometric observations of IX Dra in V (left) and B (right) bands, using the 2m telescope Rozhen. Observational data for 2460233 JD (2023-10-15 UTC date). Small-scale brightness variations are detected, identified as orbital humps with amplitude of ~0.7 mag.*

3. Comparison of flares types and their possible sources

The obtained observational results for the three binary stars, 61 Cyg A, YY Gem and IX Dra, show different behavior in their states of flares' or burst' activity. It is coming from the physical nature of the objects' structure, and as we have described in the Introduction, they are members of different classes.

The maximum values of the flare emission obtained from the TESS data during the pointed time-interval (Section 3) of 61 Cyg A is $2.65 \pm 0.0002 \times 10^{10}\ e/s$ (see previous Section). This flux rate is a bit lower than the registered large flares of the Sun, which is 10^{36} e/s, as an example of the solar event during October 2003 [Warmuth et al., 2007, Mann et al., 2009].

Comparing the results to the second star YY Gem, the flux-rate value in its maximum during the interval with a flare activity is $2.46 \pm 0.0002 \times 10^{11}\ e/s$, which is higher than the 61 Cyg A with a factor of ~ 10.

Although, it is already found [Robrade et al., 2012] the source of the observed activity in 61 Cyg A is coming from the variations in its chromosphere (or coronal properties), which is similar to the properties of the solar corona fluctuations. They also found in their results that the amplitude of the star's X-ray cycle is ~ 3 times lower than that of the Sun. The coronal cycles are typical for the G and K dwarfs, but with a smoother activity.

In both type of stars, the flares are produced in the result of the so-called magnetic reconnection, the same as considered for the Sun [Gao et al., 2008].

That's why we could compare the power of flares of our objects to those on the Sun. From the amplitude in the electron distributions, we could estimate the velocity of the particles spreading under the magnetic arc, which precedes the rising of flares.

After comparing these velocity values with the energy released during the flare, we can roughly estimate the order of magnitude of the increase in luminosity (in erg s^{-1}), compared to the average value emitted by the objects. We obtain for these orders of magnitude for both objects and it is 10^3 for 61 Cyg A and 10^4 for YY Gem, respectively. These values are larger compared to those of the Sun $(10 - 10^2)$. This result was expected, as one of the possible reasons being the smaller radii of K and M dwarfs. Therefore, the dynamo is located closer to the surface of the star. Due to the lower masses and, accordingly, the weaker gravity is more difficult to resist the effects of the dynamo. For this reason, the K- and M- dwarfs components of our two objects have a higher brightness, in terms of the activity, than that of the Sun.

The dwarf-nova nature of IX Dra exhibits in its regular outbursts' activity, seen in the TESS light curve. The outbursts are similar to those of the Sun, but less powerful. The source of bursts in IX Dra is most likely thermonuclear processes in its white dwarf companion or instability in the surrounded accretion disc. The flux-rate maximum value is $1.02 \pm 0.002 \times 10^{2}\ e/s$, which is a bit lower than the flux coming from flares. We did not observe any flares activity in this object.

4. Conclusion

In this paper we studied the appearance of solar-like activity, such as flares and bursts, in three selected binary stars by using observations of TESS and the 2m telescope of the National Astronomical Observatory Rozhen.

We presented results on the brightness variations in these three binary stars that are members of different classes: 61 Cyg; YY Gem and IX Dra. In the obtained observational data from TESS, we found manifestation of flares in the objects that contain a solar-type K - dwarf (61 Cyg A) and M - dwarfs (YY Gem) companions. During the time-intervals of the detected flares in the 61 Cyg A and YY Gem light curves, we found that the second object has more powerful emission than the first one. Comparing to the solar flares, both stars manifest higher increase in brightness than that of the Sun.

A conformation of an outburst's activity in a cycle of 2-5 days are identified in the TESS light curve of the ER UMa star IX Dra. During the outburst time, the photometric results show an appearance of orbital like hump with a period a few percent less than the orbital period of the object.

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