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CANDIDATE TRIPLE-STAR SYSTEM WITH ELLIPSOIDAL COMPONENTS DETECTED IN VULPECULA THROUGH TESS PHOTOMETRY

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Abstract: *MaGiV-1* is a candidate triple ellipsoidal star system in Vulpecula at coordinates RA(J2000) 19 : 52 : 19.13 and DEC(J2000) +23 : 29 : 59.7 classified as ELL+ELL, number 2344411 in AAVSO VSX database. Through photometry from the TESS Space Telescope, two significant periods describing the orbital times of the components were identified using the Fourier transform. The analysis led to determining $P_{\mathrm{A-BC}} = (4.269 \pm 0.213)$ d the orbital period of the A-BC pair, the primary component with the secondary component described by another pair, and $P_{\mathrm{BC}} = (0.610 \pm 0.031)$ d the orbital period of the BC pair, the inner ellipsoidal system. However, it cannot be completely ruled out that the shorter period can be explained by pulsations of one of the two components (e.g. by the GDOR type).

1 Introduction

Rotating ellipsoidal variable star systems have two stars that brightness variation shows up in photometric analysis from mutual deformation of the components by gravitational interaction. Therefore it is not generated from eclipses, but it is generated by cross-sectional area changes of the stars and it is represented by rather homogeneous light curves with an almost sinusoidal pattern and its variations are less than a tenth of a magnitude. It is very difficult to classify this type of variable star because the light curve profile does not contain the amount of information that light plots of eclipse binaries do (Morris, 1985).

This paper is about a very complex variability closely related to the ELL type (Ellipsoidal Variable Star), as it is a candidate system consisting of three ellipsoidal components describing a variation of the classical ellipsoidal binary star system. *MaGiV-1* has been defined as a 'double rotating ellipsoidal variable' (ELL+ELL) star, a triple hierarchical type system. Therefore, three stars orbiting each other simultaneously, and specifically two of these objects form a narrow binary, called inner binary, then the third companion is orbiting at a distance that far exceeds the separation length of the inner binary (Meiron, Kocsis, & Loeb, 2017). Again, the brightness variation is represented by a light curve with variability less than a tenth of a magnitude, but, from the Fourier analysis for finding the period, two significant values emerge instead of one, thus returning two distinct light curves (one child of each other). Both resulting periods represent the orbital period for each pair, just as in binary ellipsoidal variables (Jerzykiewicz *et al.*, 2011).

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2 Photometric observations

For detection of the *MaGiV-1* system, TESS photometry (Ricker *et al.*, 2014) was used, showing small brightness changes. TESS observes the sky in sectors measuring $24^\circ \times 96^\circ$. Each sector is observed for two orbits of the satellite around the Earth, or about 27 days on average. In our case, sector 41 and sector 54 were used, then photometrc observations derive from cameras as shown in Figure 1 and Figure 2:

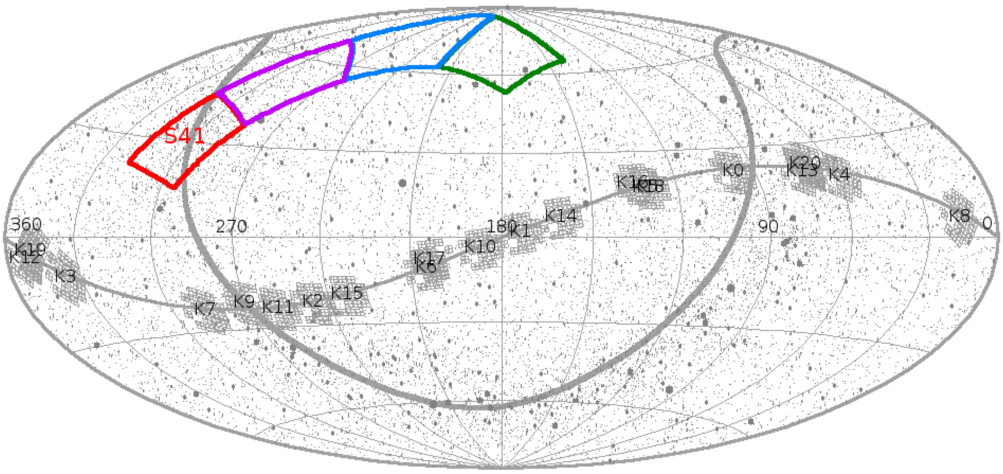

Figure 1: Map of TESS camera fields-of-view in celestial coordinates (Ricker *et al.*, 2014). Sector 41.

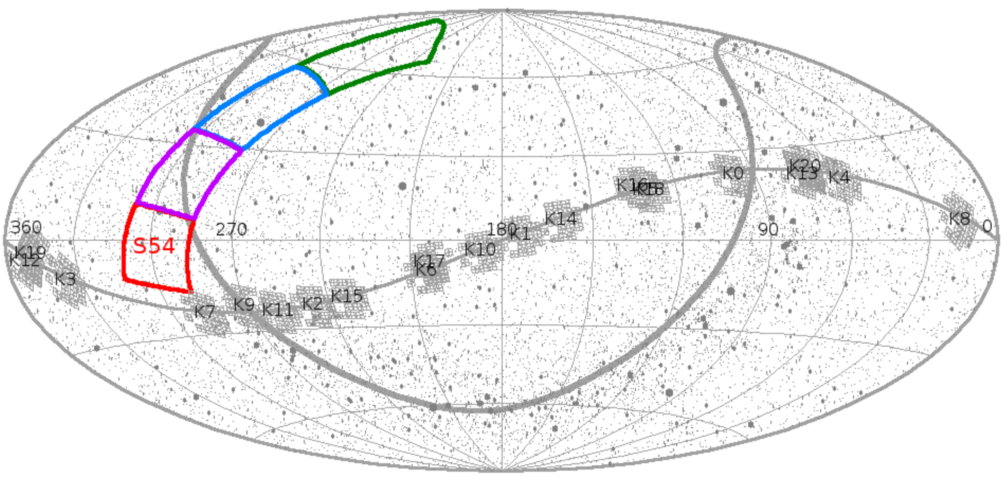

Figure 2: Map of TESS camera fields-of-view in celestial coordinates (Ricker *et al.*, 2014). Sector 54.

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Using the MAST portal (Conti *et al.*, 2011), at coordinates RA(J2000) 19 : 52 : 19.13 and DEC(J2000) +23 : 29 : 59.7, raw data were obtained for star identified as TIC 300480214. In addition, from the TESS observation FITS, the CCD camera pixels with which *MaGiV-1* was observed were obtained, and the color indicates the amount of flux in each pixel[1], as shown in Figure 3 and Figure 4 (Ricker *et al.*, 2014).

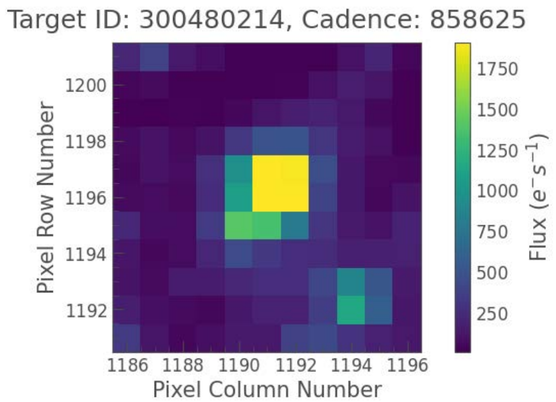

Figure 3: TESS Sector 41 pixels on the CCD camera obtained in Python with Lightkurve (Lightkurve Collaboration *et al.*, 2018) and Matplotlib (Hunter, 2007) packages.

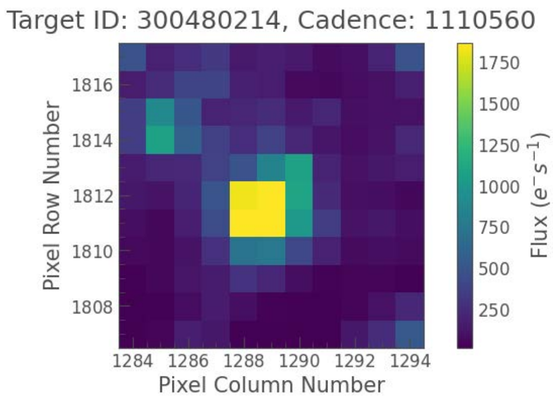

Figure 4: TESS Sector 54 pixels on the CCD camera obtained in Python with Lightkurve (Lightkurve Collaboration *et al.*, 2018) and Matplotlib (Hunter, 2007) packages.

Before the light curve analysis, the offset 2 457 000 was added to the BJD values from the fits files. (Eastman, Siverd, & Gaudi, 2010).

In addition, brightness was converted from flux to magnitudes using the following law (Bessell, 2000):

$$Mag = -2.5 \log(Flux) \tag{1}$$

Finally, a normalized magnitude around zero was used, obtained by subtracting each measure from the average of the entire data set, highlighting the very small brightness variation. It can be shown in Figure 5 and Figure 6 on 24 Jul 2021 and 9 Jul 2022 observations data respectively.

[1]Electrons per second

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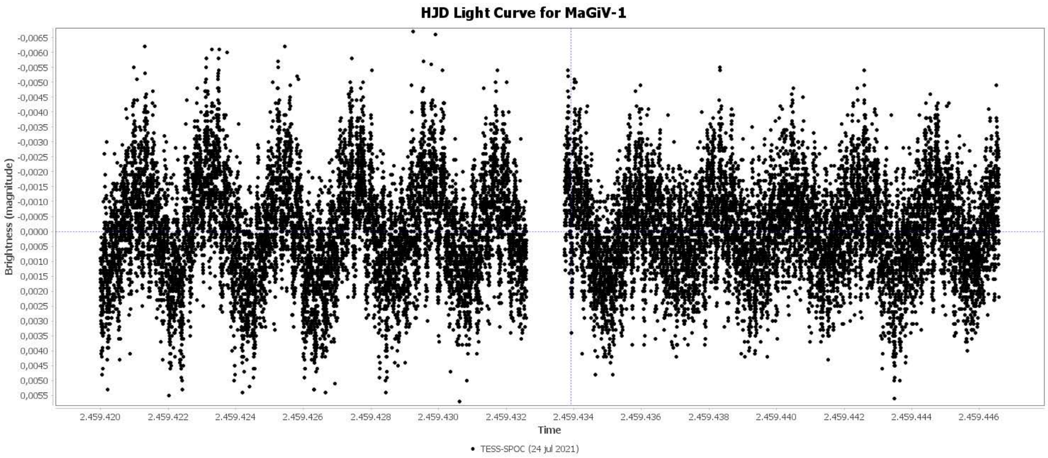

Figure 5: Full TESS Plot for *MaGiV-1* (Observation on July 24, 2021 in HJD time domain). Plot obtained with *VStar* software (Benn, 2012).

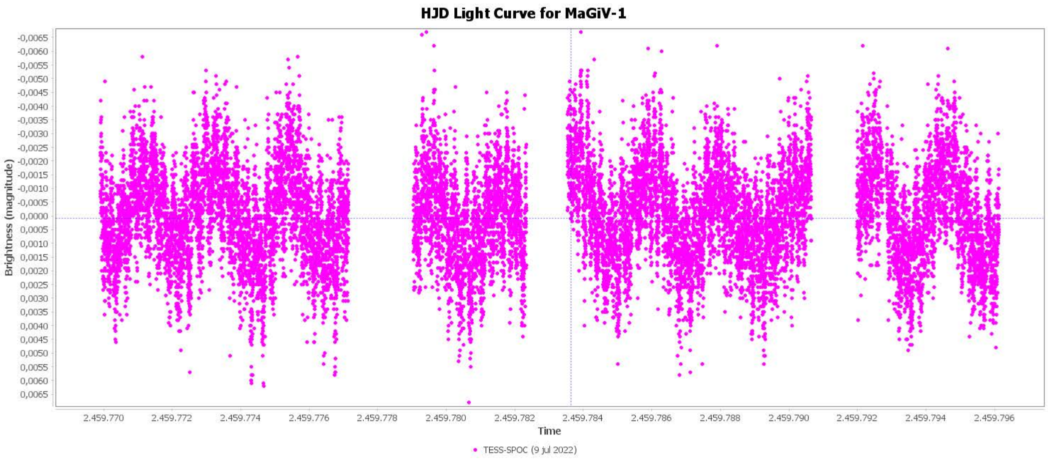

Figure 6: Full TESS Plot for *MaGiV-1* (Observation on July 9, 2022 in HJD time domain). Plot obtained with *VStar* software (Benn, 2012).

The data were processed with the Peranso software (Paunzen & Vanmunster, 2016) using the ANOVA method (Schwarzenberg-Czerny, 1996), obtaining the identification of two (or more) significant periods.

Two significant periods were obtained to describe and characterize the *MaGiV-1* candidate triple-star system in the phase domain at two observation dates (24 Jul 2021 and 9 Jul 2022). First, the light curve in Figure 7 characterized by a period $P_{\mathrm{A-BC}} = (4.269 \pm 0.213)\,\mathrm{d}$, shows two minima within an entire cycle (0 to 1) with a typical pattern of ELL variations, but including obvious and repeated oscillations along the entire plot, with 0.004 delta magnitudes. These oscillations make sense when analyzing the second light curve in Figure 8 characterized by a period $P_{\mathrm{BC}} = (0.610 \pm 0.031)\,\mathrm{d}$, showing a common plot of an ELL star systems with two minima within an entire cycle (0 to 1) and 0.003 delta magnitudes.

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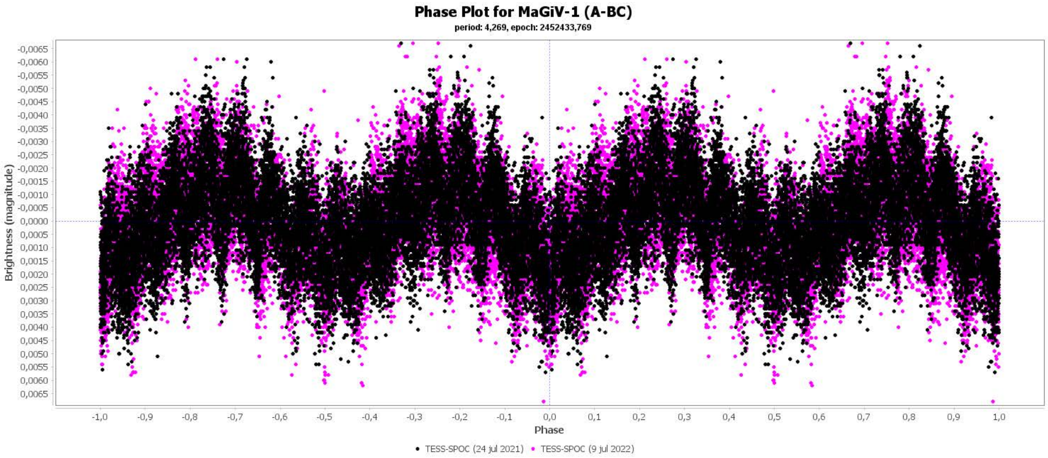

Figure 7: Phase Plot for *MaGiV-1* (1st ELL: Primary star 'A' with second couple consisting of 'B' and 'C' components). Plot obtained with *VStar* software (Benn, 2012).

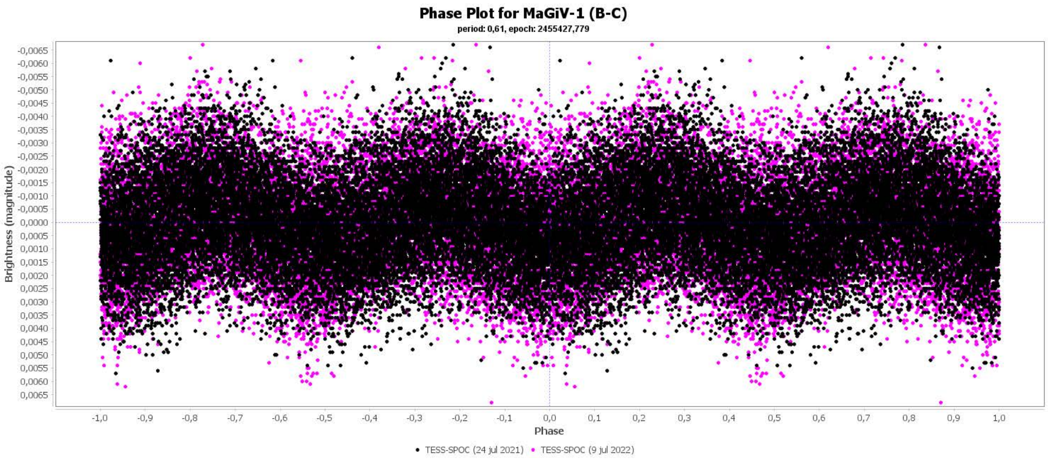

Figure 8: Phase Plot for *MaGiV-1* (2nd ELL: Couple consisting of 'B' and 'C' components). Plot obtained with *VStar* software (Benn, 2012).

Since the depths of the two minima barely differ, the true period could also be half of $P_{\rm BC}$ value, then 0.305 d.

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Analyzing the periodogram, four significant values corresponding to the fundamental peaks were evaluated.

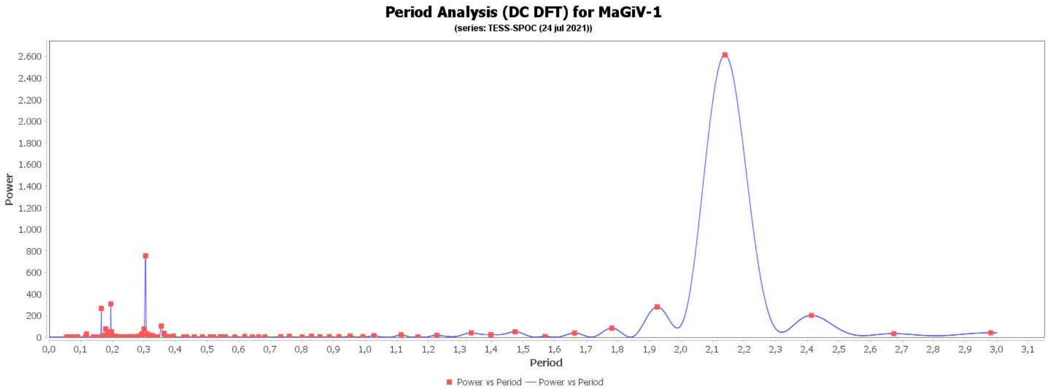

Figure 9: Periodogram for *MaGiV-1*. Plot obtained with *VStar* software (Benn, 2012).

The periodogram first shows two significant periods that could be interpreted as half of the orbital periods of the A-BC pair $P_{\text{A}-\text{BC}} = (4.269 \pm 0.213)\,\text{d}$ and the BC pair $P_{\text{BC}} = (0.610 \pm 0.031)\,\text{d}$. In addition, two periods below $< 0.2d$ are present $P_{\text{puls}_1} = (0.195 \pm 0.050)\,\text{d}$ and $P_{\text{puls}_2} = (0.165 \pm 0.050)\,\text{d}$, which could represent *Delta Scuti* type pulsations of one of the components. Since some δ Scuti stars also show pulsations in the GDOR region (Skarka *et al.*, 2022), it cannot be completely ruled out that the presumed period of the BC pair is a pulsation frequency, even if this seems unlikely.

3 Results

The variable star *MaGiV-1* was identified through data-mining from the MAST website, where it was possible to view TESS photometric observations lasting 26.594 days, therefore reference series *TESS_TIC_0000300480214_Sector_41_PDCSAP* and *TESS_TIC_0000300480214_Sector_54_PDCSAP* were used. We extracted the BJD (Barycentric Julian Date) time domain and the *detrend* flow PDCSAP_FLUX (Toonen, Hamers, & Portegies Zwart, 2016). In Download Data Products (DDP) only infrared photometry (Ic) was extracted, using FITS Viewer software, a graphical program for viewing and editing any FITS format image or table (Pence & Chai , 2020), and choosing the TIME and PDCSAP_FLUX columns (Conti *et al.*, 2011). The data thus obtained were appropriately converted and processed using the Peranso software (Paunzen & Vanmunster, 2016). As next step, we analysed it with the Fourier Transform derived by ANOVA method, using periodic orthogonal polynomials to fit the observations and statistics of variance analysis, defining their quality. This greatly improved the sensitivity of peak detection by dampening aliasing periods (Schwarzenberg-Czerny, 1996). A first period $P_{\text{A}-\text{BC}} = (4.269 \pm 0.213)\,\text{d}$ was identified with a 0.007 mag amplitude and a second period $P_{\text{BC}} = (0.610 \pm 0.031)\,\text{d}$ with a 0.003 mag amplitude. From the obtained light curves and the variable stars guidelines classification in Variable Stars Index (VSX) (Otero, 2020), it was possible to classify the *MaGiV-1* as a candidate triple star system ELL+ELL

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type candidate. Furthermore it is a triple-star system with ellipsoidal components whose luminosity variation changes with the orbital period.

Evaluating corresponding delta-magnitude for the light curves of ELL pairs respectively, it can be used the Period-Luminosity (P-L) relationship in low amplitude conditions (Pawlak *et al.*, 2014). This consideration makes it possible to define the overall brightness of two binary systems as a whole through a linear extrapolation that takes into account the orbital period. Using the relationship

$$W = -2.78(\pm 0.08) \log P + 19.30(\pm 0.18) \tag{2}$$

the following results were obtained

$$W_{\mathrm{BC}} = (19.90 \pm 0.11)\mathrm{mag} \tag{3}$$

$$W_{\mathrm{A-BC}} = (17.55 \pm 0.16)\mathrm{mag} \tag{4}$$

Where W_{BC} is the overall brightness of the inner binary system and $W_{\mathrm{A-BC}}$ is the overall brightness of the outer binary system. With these results, the '*giant-giant*' type components were defined, in according by the linear extrapolation model proposed for low-amplitudes.

Finally, the distance of *MaGiV-1* was obtained through the relationship linking it with the magnitudes resulting from the photometric analysis

$$d = 10^{(m_{\mathrm{v}} - M_{\mathrm{v}} + 5 - A_{\mathrm{v}})/5} \tag{5}$$

where m_{v} and M_{v} are relative and absolute magnitudes, respectively.

The information provided by *Gaia* regarding the parallax $p = 0.835079181$ mas, the extinction $A_{\mathrm{v}} = (1.40 \pm 0.56)$ mag and the magnitude of source $m = (10.144 \pm 0.557)$ mag was used (Hughes, 2006).

The evaluated distance is $d = (629 \pm 245)$ pc and comparing it to the *Gaia* distance $d_{\mathrm{Gaia}} = 1018$ pc, shows an underestimation, because the *Gaia* distance is derived from the parallax, brings with it a more significant detection uncertainty. The index $RUWE = 2.387$ (Gaia Collaboration, 2020) is significantly larger than one (value of high probability).

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