Astronomical and Astrophysical Transactions (*AApTr*), 2025, Vol. 35, Issue 3, pp. 269–274,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

Dual signatures in binary light curves: eccentricity and flare activity in TESS data

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Received 27 April, 2025; accepted 11 June, 2025

Supervised machine learning methods require sufficiently representative samples of input data, particularly observational light curves or their characteristic parameters. To compile such samples, data from multiple astronomical surveys are typically employed. However, preparing a reliable training set is often a non-trivial task, as it demands considerable resources: time and the expertise of qualified astronomers to classify and determine key parameters necessary for building an effective machine learning model. In this work, we present a sample of objects with two distinctive features in their light curves, selected from the catalog of eclipsing binaries observed by the TESS space mission. These features are (i) orbital eccentricity, which visually manifests as a deviation of the secondary eclipse from the midpoint between successive primary eclipses, and (ii) the simultaneous presence of flare activity. An initial set of 38 candidates was selected, of which 20 systems were ultimately included in the final sample. Based on calculated eclipse timings, we derived preliminary values of the secondary minimum phase (assuming the primary eclipse occurs at phase zero), as well as the times of peak flare events observed in the light curves of these binary systems.

Keywords: Stars: variables – binaries: eclipsing – binaries: eccentricities – binaries: flares

1 Introduction

The study of eclipsing binaries (EBs) is essential for understanding fundamental stellar properties and processes in astrophysics. Traditionally, astronomers rely on complex modelling tools to derive the physical parameters of EBs. However, these models are often computationally intensive due to the large number of parameters involved, which significantly limits the scope and efficiency of EB analysis. Supervised machine learning (ML) techniques offer a promising alternative by drastically reducing modelling time, from several days to mere seconds, enabling the efficient analysis of hundreds of thousands of EB light curves. Achieving accurate predictions of EB light curve morphologies across a wide parameter space, however, requires representative

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and diverse training samples, including real observations cataloged across multiple surveys. Furthermore, understanding how different physical effects and light curve features influence model performance is key to developing robust ML applications in stellar astrophysics. Photometric parameters that can be derived solely from light curves include relative quantities, such as the radius-to-temperature ratio and the mass ratio, as well as absolute parameters like eccentricity, argument of periastron, and orbital inclination (Wrona et al. 2025). In this study, we present a sample of TESS eclipsing binary (EB) light curves that simultaneously exhibit orbital eccentricity and individual flare events. Such systems are of particular interest because tidally driven oscillations can only occur in eccentric binaries. These oscillations differ significantly from self-excited stellar pulsations, as they are resonantly excited by the periodically varying tidal potential induced by the companion star. Dynamical tides in eccentric binaries can exchange energy and angular momentum with the orbital motion, thereby directly influencing the long-term evolution of the system (Kołaczek-Szymański et al. 2024). However, the extent to which these tidal effects impact the magnetic activity cycles of individual stars remains poorly understood.

2 Data and analysis

A detailed study of various classes of eclipsing binary stars is possible using data from the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015; Prša et al. 2022). Launched in April 2018, TESS monitored approximately 200,000 bright stars across the sky during its 2-year primary mission, using a 2-min short cadence. Although originally designed for detecting exoplanets around bright host stars, TESS has evolved into a stellar variability survey, now covering about 85% of the sky. The TESS data include light curves sampled at intervals of 30 min, 10 min, or 200 sec, depending on the sector. Each sector spans $24^\circ \times 96^\circ$ of the sky and is observed for about one month. Furthermore, the multi-sector TESS data provide a multi-year observational baseline that is well-suited for studying long-term variability in stellar light curves. TESS is currently operating in its extended mission, during which targets are observed with 2-min and 20-sec cadences, and full-frame images are acquired every 10 min. Prša et al. (2022) published a catalog of 4,843 eclipsing binaries observed with short cadence from the TESS survey. The data are publicly available from two official sources: the project's main webpage (http://tessEBs.villanova.edu) and at MAST as a High Level Science Product via DOI 10.17909/t9-9gm4-fx302. To date, we have visually inspected approximately half of the TESS eclipsing binary (EB) catalog, corresponding to IDs in the range from 185259483 to 117397619 – a total of 2,000 light curves. We selected 38 systems that, at first glance, exhibit signs of orbital eccentricity (namely, a displacement of the secondary eclipse time relative to the midpoint between successive primary eclipses) and also show flare activity. Additionally, the selected sample proved to be rich in other interesting phenomena, such as multiplicity and stellar pulsations. To determine the times of eclipses and the peak fluxes of flares, we collected all publicly available TESS light curves. The 2-min cadence light curve data are typically provided as Simple Aperture Photometry (SAP) and Pre-search Data Conditioning SAP (PDCSAP) fluxes (Jenkins et al. 2016). The latter are derived from SAP fluxes by removing long-term instrumental trends using Co-trending Basis

Vectors (CBVs). However, as noted by Yuangui Yang (2024), PDCSAP data are often worse than SAP, and a portion of PDCSAP data was deleted. After inspecting all the light curves in our sample, SAP data were preferred for most objects. To determine the times of eclipse minima, we approximated the eclipse profiles using the lmfit package[1] (Newville et al. 2014), which implements the Levenberg–Marquardt minimization algorithm and the built-in Peak-like models (class "GaussianModel" for the partial minima and class "RectangleModel" – Step-like models – for several cases of the full minima). The timing of the minima was then used to calculate the phase difference between consecutive secondary and primary eclipses. Assuming the primary eclipse occurs at phase zero, the phase of the secondary eclipse was computed as the average of these phase differences, and the uncertainty was estimated as the standard deviation. Systems with a secondary minimum phase ≥ 0.51 were considered to have non-zero orbital eccentricity. The flare peak time was estimated by locating the maximum flux within a defined window surrounding the detection.

3 Results

Table 1 presents some information for our preliminary sample of eccentric eclipsing binaries with observed flare events. Columns 1 and 7 list the TIC (TESS Input Catalog) identifiers and SIMBAD object names, respectively. Columns 2 through 4 provide the orbital periods, initial epochs BJD0 (given as BJD – 2457000) and morphological coefficients (MC; it ranges from 0 for detached systems to 1 for ellipsoidal or systems of uncertain type) from EB TESS catalog. In column 5, we provide the references that report published estimates of the orbital eccentricity or the quantity $e \cos \omega$. Column 6 shows the measured phases of the secondary minima with their associated uncertainties (in parentheses). The remaining systems from the initial sample were not included to Table 1 for the following reasons: (i) the secondary eclipse phases were <0.51, indicating nearly circular orbits, even if some eccentricity estimates are available in the literature, or (ii) the published BJD0 values were found to be erroneous and once corrected, the systems showed no significant eccentricity. Moreover, the ephemerides given in Table 1 should also be considered as preliminary. For all 38 systems in our initial sample, we determined the peak times of detected flare events from their light curves. These measurements are available at the following URL https://doi.org/10.5281/zenodo.15263916, where the first column lists the TIC ID and the second column gives the flare peak times (BJD – 2457000).

Thereby, the final sample includes 20 systems with periods in the range of 0.374–34.927 days, and TESS magnitudes between 8.0 and 13.6 mag. The systems span a broad range of morphological coefficients and effective temperatures, from 3181 K to 5929 K. Figure 1 shows the color–magnitude diagram (CMD) with the selected systems overlaid.

Seven systems in our sample are located within 100 pc from the Sun, based on Gaia parallax data: TIC 142979644, 309528896, 360205899, 232629077, 230086768, 160150808, and 180412528. Several systems show evidence of pulsational activity, although further analysis is required to confirm their nature. Documented flares for

[1] https://lmfit.github.io/lmfit-py/

systems in this sample can also be found in previous studies (Tu et al. 2022; Yang et al. 2023).

Table 1 Sample of eccentric eclipsing binaries with detected flare events from the TESS EB catalog.

TIC ID	P (days)	BJD0 (days)	MC	Phase	Ref. (*)	SIMBAD name
032449963	6.5205	1574.6948	0.15	0.5244(1)	(c)	HD 110086
047757785	15.6793	1686.5721	0.33	0.24482(6)		HD 172884
049534600	7.9490	1662.0530	0.16	0.4501(2)		HD 166706
140659980	9.4401	1602.0373	0.08	0.473(1)		HD 31547
142979644	4.1790	1687.5456	0.11	0.5179(2)		RX J1206.9+7007B
157770450	3.2895	1685.3101	0.57	0.486(5)		V* MW Dra
160150808	0.3740	1600.0941	0.59	0.76(2)		CRTS J144919.3-381017
162035117	13.1504	1716.8634	0.15	0.1787(1)		Wolf 1156
179966966	1.5481	1601.5917	0.79	0.648(1)		TYC 7809-1741-1
230086768	34.9269	1771.0571	0.03	0.74639(2)		LSPM J1626+6608E
232629077	3.6550	1684.3654	0.16	0.4823(2)	(a)	HD 164025
238892775	0.4827	1325.6997	0.93	0.45(3)		CD-72 126
260128333	14.6086	1585.1666	0.12	0.453(2)	(a)	BEBOP-1c
261335113	8.1306	1322.1352	0.06	0.53704(4)		UCAC4 047-003560
287085893	0.9350	1765.1190	0.79	0.51(1)		RX J1653.2+7015
303427297	4.2974	1569.9457	0.19	0.5284(4)	(c)	TYC 8623-776-1
317839169	4.6689	1765.1010	0.33	0.773(2)	(b)	BD+71 1213
360205899	0.4285	1544.4109	0.66	0.5137(9)		2MASS J09282336-6414548
366072761	7.6596	1766.5770	0.09	0.484655(1)		UCAC4 800-039002
441694629	7.3299	1716.6629	0.08	0.48756(3)		TYC 3852-109-1

(*): (a) Arenou et al. (2023), (b) Vallenari et al. (2023), (c) Justesen et al. (2021)

4 Conclusion

In this work, we presented the preliminary sample of 20 eclipsing binary systems from the TESS EB catalog that exhibit both orbital eccentricity and flare activity. By analyzing initially selected 38 TESS light curves, we identified systems with significant displacement of secondary eclipses, indicating non-zero eccentricities, and determined the timing of flare peaks. Our approach combines morphological light curve analysis with flare detection, providing a valuable dataset for understanding the interplay between orbital dynamics and magnetic activity in close binary systems.

The next stages of this study will include extending the analysis to the remaining portion of the TESS EB catalog in order to identify additional eccentric systems and flare-active binaries. We will compile a complete list of measured eclipse minima times and calculate the corresponding $O - C$ (Observed minus Calculated) values to investigate potential period variations, apsidal motion, or the presence of third bodies. In addition, we plan to release a comprehensive catalog of flare peak times for all identified systems, provided such data are not already available in existing databases.

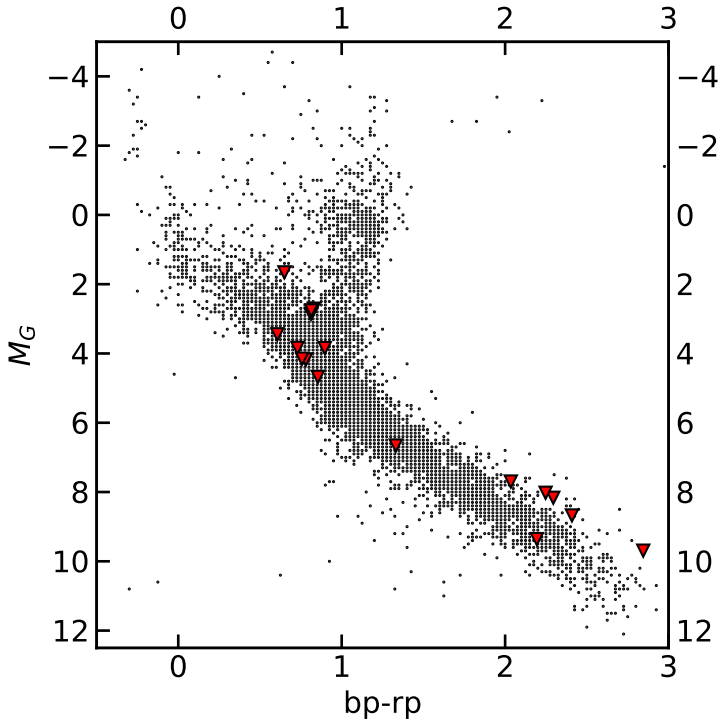


Figure 1 Extinction-corrected color–magnitude diagram (CMD) showing the positions of the 20 eclipsing binary systems analyzed in this study. The grey points represent 100,000 randomly selected stars from Gaia DR3 (with high-quality parallaxes: $parallax_over_error>5$).

These efforts aim to expand the current census of dynamically and magnetically active binaries and contribute to a deeper understanding of their evolutionary status.

Acknowledgements

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This research has made use of the VizieR catalog access tool, CDS, Strasbourg, France. The original description of the VizieR service was published in 2000, A&A S 143, 23. This work has made use of data from the European Space Agency (ESA) mission Gaia[2], processed by the Gaia Data Processing and Analysis Consortium (DPAC[3]). Funding for the DPAC has been provided by national institutions, in particular, the institutions participating in the Gaia Multilateral Agreement. This paper includes data collected with the TESS mission, obtained from the Mikulski Archive for Space Telescopes (MAST) at the Space Telescope Science Institute (STScI). Funding for the TESS mission was provided by the NASA Explorer Program. STScI is operated by the Association of Universities for Research in Astronomy, Inc., under

[2]https://www.cosmos.esa.int/gaia
[3]https://www.cosmos.esa.int/web/gaia/dpac/consortium

the NASA contract NAS 5–26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX13AC07G and by other grants and contracts. The authors thank the developers of `lmfit`.

Funding

The work was carried out with the support of the state budget of the Republic of Uzbekistan.

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